Claims 1, 11-13 and 25-26 have been deleted and rewritten as new claims 31-33 and 34-36. New claims 37 and 38 have been added.

The phrase "GPS signal receiver/processor" used in claims 9, 23 and 27-28 is introduced on page 8, line 24, of the specification and is used in the art to refer to apparatus that receives GPS signals, directly or indirectly, from one or more GPS satellites, analyzes and processes these GPS signals, and determines the location of the GPS receiver/processor. Tom Logsdon, in The NAVSTAR Global Positioning System,Van Nostrand Reinhold, 1992, pp. 17-75, divides a NAVSTAR GPS into three segments: space segment (satellites and radio downlinks), user segment (ground station antenna, receiver/processor and control display) and master control segment (master station). A photocopy of this discussion is enclosed with, and incorporated by reference in, this Amendment And Response. The GPS and GLONASS navigation and positioning systems are also discussed in some detail in the patent application, page 12, line 2 - page 14, line 11. Although the GPS receiver/processor might be adequately covered in means-plus-function, the Applicant uses the particular phrase "GPS signal antenna and receiver/processor" because this phrase is well understood with reference to NAVSTAR global positioning systems.

The term "signal antenna and receiver/processor" used in claims 31 and 34 refer, among other things, to a GPS or LORAN signal antenna and receiver/processor. Here, the signal antenna receives signals containing information from which the location of the antenna (or the attached vehicle) can be determined and passes these signals to the signal receiver/processor for such determination. These signals may be received from satellites, where a system such as GPS is used, or from transmitters located adjacent to the Earth's surface and spaced apart from the vehicle, where a system such as LORAN is used. Methods used by a signal receiver/processor in determining the location of the signal antenna (or the attached vehicle) for GPS or for LORAN are discussed, respectively, in Guide to GPS Positioning, referenced in the patent application, in the book by Logsdon, op. cit., and in U.S./ Patent No. 3,665,086 (discussing LORAN), issued to Magee and referenced in the patent application. This characterization also applies to the terms "signal antenna" and/or "signal receiver/processor" used in claims 6-8

and 20-22

Claims 11-12 and 25-26 have been deleted and rewritten as new independent claims 32-33 and 35-36, respectively, in order to set forth more explicitly the functions and components of the "receiver/processor" used in such claims.

If the Examiner prefers, the "receiver/processor" referred to in claims 6-10, 20-24 and 31-36 can be restated in means-plus-function language. However, the Applicant believes that the new language used in these claims is sufficiently definite to apprise a person of ordinary skill in the art what is intended, in the context used, when the terms "signal antenna" and/or "signal receiver/processor" are used in such claims.

The "controller/modem" used in claims 1, 6, 13 and 20 is introduced and discussed at page 8, line 23, page 9, lines 13-16, and page 10, lines 1-27, and refers to a module that: (1) receives notification from a page responder in a vehicle that a page request has been received; (2) interrogates the location determination system (e.g., GPS, GLONASS, gyroscope or local magnetic field sensors), carried on the vehicle, for the present or last known location of the vehicle; (3) receives this vehicle location information from the location determination system; and (4) causes a cellular telephone or similar communications system, carried on the vehicle, to place a call to a selected station and to transmit the vehicle's present or last known location to the selected station. Operation of the controller/modem is similar for any location determination system used as part of the invention recited in claims 1, 6, 13 and 20 and new claims 29-31.

The phrase "vehicle location or paging service" introduced in claim 1, at lines 8 and 14-15, as amended, is introduced and discussed on page 7, lines 8-9, page 8, lines 16-22, page 9, lines 5-12 and 25-30, page 10, lines 1 and 16-24. This phrase refers to a central station that may: (1) receive notification that a vehicle is missing or has been tampered with and/or moved; (2) initiates a vehicle pager request (broadcast by radio wave or similar communication medium) requesting the present location of this vehicle; (3) receives a response, transmitted by a cellular telephone or similar communication medium, notifying the central station of the present location of this vehicle; and (4) provides information on this vehicle to a user of the vehicle location service or paging service.

The written material relied upon for defining the terms "receiver/processor", "controller/modem" and "vehicle location or paging service" is contained in the specification, in references cited in the specification, or in the cited discussion in the Logsdon book, op. cit. The Applicant relies upon this material in the claims that use or rely upon these terms, in order to avoid increasing the length of the independent claims beyond their already substantial length. However, if the Examiner believes recitation of additional detail is required in the claims, the Applicant will amend the claims and add the defining material recited above to the claims.

The Examiner rejects claims 1-26 under 35 U.S.C. 102(b) as anticipated by U.S. Patent No. 5,055,851, issued to Sheffer, by U.S. Patent No. 5,003,317, issued to Gray et al, and by U.S. Patent No. 4,947,151, issued to Rosenberger. The Examiner rejects claim 28 under 35 U.S.C. 102(b) as anticipated by U.S. Patent No. 5,043,736, issued to Darnell et al.

The Sheffer patent discloses a vehicle location system in which a vehicle generates an alarm signal that is received by a fixed array of cellular transceivers at four or more cellular sites. See Figures 3 and 4A of the Sheffer patent. Each cellular transceiver has an alarm signal detector and is capable of detecting signal strength, which is expected to differ from one cellular site to another for an alarm signal transmitted by a vehicle. Each cellular transceiver then transmits an information signal to a central station indicating (1) that an alarm signal has been received from a vehicle; (2) the identity of the vehicle; and (3) the strength of the receive alarm signal. The central station: (1) compares the reported signal strengths for the given alarm signal from each cellular transceiver; (2) selects the four strongest reported alarms signals; (3) uses inverse square law modelling to determine an estimated radius r corresponding to the distance of each of these four cellular transceivers from the source of the alarm signal; (4) forms an arcuate rectangle, using arcs of four circles with the four estimated radii r; and (5) determines that the vehicle is located at the "center" of this arcuate rectangle. No estimate is given of the possible range of diameters of this arcuate rectangle. Once the vehicle alarm signal system is activated, the vehicle continues to transmit its alarm signal and the cellular transceivers continue to transmit their respective

alarm signal strengths, in order to allow determination of the approximate location of a stationary or moving vehicle.

The invention disclosed in the Sheffer patent differs from the invention recited in independent claims 31-36 (replacing independent claims 1 and 13) of the subject patent application in the following features. (1) The Sheffer invention requires use of four or more cellular sites or regions (shown in Figure 4A) and requires positioning of a cellular transceiver at a fixed position in each of these cellular regions. The invention recited in claims 31-36 of the patent application does not require or make any use of any fixed (or moving) array of cellular transceivers, except for a single cellular or similar communications device ("cellular telephone") carried on the vehicle itself.

(2) The Sheffer invention relies upon measurement of transmitted signal strength by each cellular transceiver and upon continuous reporting of that signal strength to the central station, in order to determine the present location of the vehicle. The invention recited in claims 31-36 of the patent application does not measure or use transmitted signal strength for determination of vehicle location. The vehicle location is determined at the vehicle itself by a GPS, GLONASS, gyroscope or local magnetic field strength sensor and is reported to a central station by transmission from a single cellular means. The vehicle location is already determined when this transmission occurs and need not be (re)determined at the central station. Optionally, the unprocessed vehicle location information can be transmitted by the single cellular means, and the vehicle location cen be finally determined at the central station. However, this requires only transmission by a single cellular means located on the vehicle itself, not transmission from four or more cellular transceivers at fixed and known locations.

(3) Each cellular transceiver used in the Sheffer invention must (a) receive an alarm signal transmitted by the vehicle, (b) measure the signal strength of this alarm signal and (c) transmit a signal indicating that an alarm signal has been received and the signal strength of that signal. The cellular telephone recited in claims 31-36 of the patent application merely receives a command to transmit and transmits the vehicle location information provided for it by the receiver/processor (or by the controller/modem); no measurement of signal strength is required by the

cellular means or by any other component of the invention. (4) The Sheffer invention requires that the vehicle continue to transmit the alarm signal after the alarm is activated, at least once every five seconds, according to column 10 of the Sheffer patent specification. The invention recited in dependent claims 6, 7, 20 and 21 of the patent application allows variation of the time interval of vehicle location reporting, in order to conserve current or power in the power supply that drives the vehicle location reporting system carried on the vehicle. The Sheffer invention and the invention recited in claims 31-36 of the patent application work in very different manners. Because of these substantial differences, the Applicant submits that the disclosures in the Sheffer patent do not anticipate the invention(s) recited in claims 31-36 of the patent application.

The Gray et al patent discloses a stolen vehicle recovery system in which a vehicle carries a transceiver for periodically transmitting a coded signal indicating (1) the identity of the vehicle and (2) whether the vehicle is stationary or moving. The vehicle transceiver periodically receives an authorization signal from an on-board authorization device, such as a keyboard, carried on the vehicle itself. If the proper authorization signal is not received by the transceiver, the transceiver begins transmitting the coded signal. This coded signal is received by a scanning receiver located at a remote site. Receipt of this coded signal activates an array of two or more direction-finding antennas that scan the local region and determine the present location of the vehicle by triangulation.

The Gray et al patent differs from the invention recited in claims 31-36 of the subject patent application in the following features. (1) The Gray et al invention requires periodic presentation of an authorization signal by an occupant or user of the vehicle. If this authorization signal is not presented at appropriate times to a transceiver carried on the vehicle, the transceiver begins transmitting the coded signal. The invention recited in claims 31-36 of the patent application does not require presentation of any authorization signal. The vehicle location system carried on the vehicle responds to receipt of a paging request, transmitted from a vehicle location or paging central station located elsewhere, and determines and transmits information on the present location of the vehicle to this central station.

(2) The central station in the Gray et al invention receives a coded signal indicating the identity of the vehicle and the fact that no authorization signal has been received but does not receive directly from the vehicle transceiver information on the present location of the vehicle. The central station recited in claims 31-36 of the patent application receives information on the vehicle identity and present location of the vehicle directly from the cellular telephone carried on the vehicle.

(3) The Gray et al invention requires use of two or more direction-finding antennas to determine the location of the vehicle, after receipt of the coded signal from the vehicle transceiver. Receipt and post-processing of other signals, after receipt of the coded signal from the vehicle transceiver, is thus required to determine the present location of the vehicle. The invention recited in claims 31-36 of the patent application uses no direction-finding antennas for the vehicle and does not require receipt of any other transmitted signals after receipt of a vehicle location information signal from the cellular means carried on the vehicle. (4) The Gray et al invention requires that the vehicle continue to transmit the coded signal after the vehicle transceiver is activated, thus draining current or power from the power supply. The invention recited in dependent claims 6, 7, 20 and 21 of the patent application allows variation of the time interval of vehicle location reporting, in order to conserve current or power in the power supply that drives the vehicle location reporting system carried on the vehicle. The Gray et al invention and the invention recited in claims 31-36 of the patent application work in very different manners. Because of these substantial differences, the Applicant submits that the disclosures in the Gray et al patent do not anticipate the invention(s) recited in claims 31-36 of the patent application.

The Rosenberger patent discloses a motion and tampering alarm system, mounted in a pneumatically pressurized tire, that transmits a radio alarm signal when the tire is in motion or is being tampered with, absent authorization that is provided or withdrawn by receipt of encrypted radio signals. The alarm system includes a transceiver mounted inside the tire, a microprocessor(1) to receive and process the encrypted signals that enable and disable the alarm system and (2) to transmit the alarm signal at appropriate times, and a power supply. The alarm

signal may be received by a cellular telephone system or other system for localization of the signal, by means that are unspecified in the Rosenberger patent. The Rosenberger invention differs from the invention recited in claims 31-36 of the subject patent application in the following manners. (1) The Rosenberger invention uses encrypted radio signals to activate and deactivate the alarm signal. Absent deactivation of the alarm system (for example, by forgetfulness), the alarm signal will be transmitted whenever the tire is worked on or used for transportation or other legitimate purposes, even by the tire owner. The invention recited in claims 31-36 uses no encrypted radio messages and is activated and begins reporting present vehicle location only when the vehicle receives a vehicle location paging request from a vehicle location or paging central station.

(2) The alarm system in the Rosenberger invention does not itself report its location or even the identity of the tire that carries the alarm system. The present location of this alarm system must be determined by receipt and analysis of the alarm signal by apparatus that is not specified or discussed in the Rosenberger patent. In the invention recited in claims 1-26 of the patent application, the signal transmitted by the cellular telephone carried on the vehicle (a) identifies the vehicle and (b) provides all information required to determine the vehicle's present location, with no further signal transmission required.

(3) The Rosenberger invention requires that the alarm system continue to transmit the alarm signal after the alarm system is activated, thus draining current or power from the power supply. The invention recited in dependent claims 6, 7, 20 and 21 of the patent application allows variation of the time interval of vehicle location reporting, in order to conserve current or power in the power supply that drives the vehicle location reporting system carried on the vehicle. The Rosenberger invention and the invention recited in claims 31-36 of the patent application work in very different manners. Because of these substantial differences, the Applicant submits that the disclosures in the Rosenberger patent do not anticipate the invention(s) recited in claims 31-36 of the patent application.

The Darnell et al patent discloses a user location system, whereby a user (person or vehicle) carries a GPS unit that continually determines the user's location. User location information is continually transmitted by a cellular

telephone to a central station that determines and visually displays the present locations of a plurality of users. This invention appears to be intended for use in fleet management, where the present locations of a plurality of vehicles are to be determined, without regard to whether the vehicle is being moved or tampered with in an unauthorized manner.

Independent claims 27 and 28 focus on use of a GPS type of location system, and new dependent claims 29 and 30 each add the feature that at least one of the signal antenna, the receiver/processor and the cellular telephone is concealed on the vehicle.

The Darnell et al invention differs from the invention disclosed in claims 27-30 of the subject patent application in the following manners. (1) The Darnell et al user location system requires that that GPS unit always be activated and that the associated cellular unit always be transmitting the present location of the user who carries that GPS unit. In the invention recited in claims 27-30 of the patent application, a GPS or other location determining unit and a cellular means are carried on a vehicle, but the combined location determining unit and cellular means are activated only when a receiver carried on the vehicle receives a vehicle location or paging request signal from a central station. The electrical current or power supplied by a power supply for this combination is thus conserved through maintenance of the system in a "sleep mode" most of the time. The system is activated only when (a) the vehicle is moved in an unauthorized manner or (b) some other specified event occurs, as sensed by an event sensor located on or adjacent to the vehicle. (2) The Darnell et al user location system is not hidden, because its presence and use are considered to be natural and expected. In the invention recited in dependent claims 29-30 of the patent application, the vehicle location reporting system carried on the vehicle is hidden or camouflaged, because activation of this system is implemented only under circumstances in which the present "user" of the vehicle should not be alerted to the presence or use of this system to determine the present vehicle location.

The invention disclosed in the Darnell et al patent and the invention recited in claims 27-30 of the patent application are intended to operate in different and dissimilar environments and thus do not operate in similar manners. Because of the

substantial differences in the environments and in manners of use of these two inventions, the Applicant submits that the disclosures in the Darnell et al patent do not anticipate the invention(s) recited in claims 27-30 of the patent application.

In all the claims 2-10, 14-24 and 27-36 of the patent application, a vehicle location system carried on the vehicle: (1) is activated by a paging signal or similar radiowave request received from a central station, or by an event sensor carried on the vehicle; (2) determines the present location of the vehicle from information provided by the vehicle location system itself, with no additional information required; and (3) transmits this vehicle location information to a designated central station (vehicle location service or paging service) to provide such information for a requestor. The designated central station need not do any further processing of this received information to determine the present vehicle location. In these respects, the invention set forth in claims 2-10, 14-24 and 27-36 of the patent application differs from each of the patents cited and applied by the Examiner.

New claims 37-38 are similar to the claims 31-36 but focus on the central operative features of the invention. The Applicant believes that, for the reasons adduced above, claims 37-38 are also allowable over the references cited and applied by the Examiner.

For the foregoing reasons, the Applicant submits that claims 2-10, 14-24 and 27-28, as amended, and new claims 29-38 are patentable over, and are not anticipated by, the patents cited and applied by the Examiner. The Applicant requests that the Examiner pass the patent application, as amended, to issue as a U.S. patent.

Respectfully Submitted,
John Schipper
John Schipper
Patent attorney for Applicant

#3
S.N. 978,272

The Navstar Global Positioning System

Tom Logsdon

VNR VAN NOSTRAND REINHOLD
New York

Lit[redacted] Congress Catalog Card Number 92-10521
ISB[redacted]2-01040-0

Printed in the United States of America

Van Nostrand Reinhold
115 Fifth Avenue
New York, New York 10003

Chapman and Hall
2-6 Boundary Row
London, SE 1 8HN, England

Thomas Nelson Australia
102 Dodds Street
South Melbourne 3205
Vi[redacted]ustralia

Nel[redacted]nada
1120 [redacted]mount Road
Scarborough, Ontario M1K 5G4, Canada

16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging-in-Publication Data

Logsdon, Tom, 1937–
The Navstar global positioning system / by Tom Logsdon.
p. cm.
Includes bibliographical references and index.
ISBN 0-442-01040-0
1. Artificial satellites in navigation—United States. 2. Global Positioning System. I. Title.
TL798.N3L64 1992
629.04'5—dc20 92-10521
CIP

Dedication

To Chad, who someday may be using the modulated signals from the Navstar satellites to guide his noisy trailer truck along the Interstate.

Contents

enough to be launched into space. The rubidium atomic clocks onboard the GPS satellites weigh only about 15 pounds, draw 40 watts of power, and maintain timing stability to within 0.2 parts per billion. The cesium atomic clocks, which are slightly more stable, weigh about 30 pounds each.

Practical Benefits for All Mankind

With a fully operational Navstar satellite constellation, no one ever need be lost again. The signals from the satellites—which are available free of charge to anyone, anywhere—have already revolutionized surveying, precision timekeeping, and modern military operations. They are being used in large numbers all over the globe to fix the positions of ships, planes, boats, trains, satellites, even ordinary family Chevrolets.

Navstar receiver costs have dropped dramatically. A decade ago the cheapest available models sold for $140,000 each. Today's least expensive versions are going for less than $2,000 and ordinary hikers and boat owners have been snapping them up by the thousands. Knowledgeable experts maintain that some of tomorrow's models may retail for only $500 each or, perhaps, even less. With costs that low, future applications will be limited only by the dreams and imaginations of those who spend their days—and nights—coming up with clever new ways to use them.

2

The Navstar GPS

The Navstar GPS is a satellite-based radionavigation system that provides continuous global coverage to an unlimited number of users who are equipped with receivers capable of processing the signals being broadcast by the satellites. As Figure 2.1 indicates, the system can be broken into three major pieces or segments:

1. The space segment
2. The user segment
3. The control segment

The fully operational *space segment* will consist of 21 Block II satellites plus 3 active on-orbit spares arranged in six 55-degree orbit planes 10,898 nautical miles above the earth. Each Navstar satellite transmits a precisely timed binary pulse train together with a set of ephemeris constants defining its current orbit.

The *user segment* consists of tens of thousands of Navstar receivers located on the ground, in the air, and aboard ships, together with a few aboard orbiting satellites. A Navstar receiver (user set) picks up the precisely timed signals from four or more satellites—either simultaneously or sequentially—and then computer-processes the results to determine its current position.

If the Navstar satellites could permanently track their precise orbital locations and the exact time, no other hardware elements would be required. Unfortunately, the satellites tend to lose track of where they are and what time it is, so a computer-driven *control segment* is necessary. The control segment includes a group of unmanned monitor stations that track each Navstar satellite as it travels across the sky. This information is then used to determine the satellite's orbital elements, together with any timing errors in its onboard atomic clocks. The resulting corrections are then sent to one of

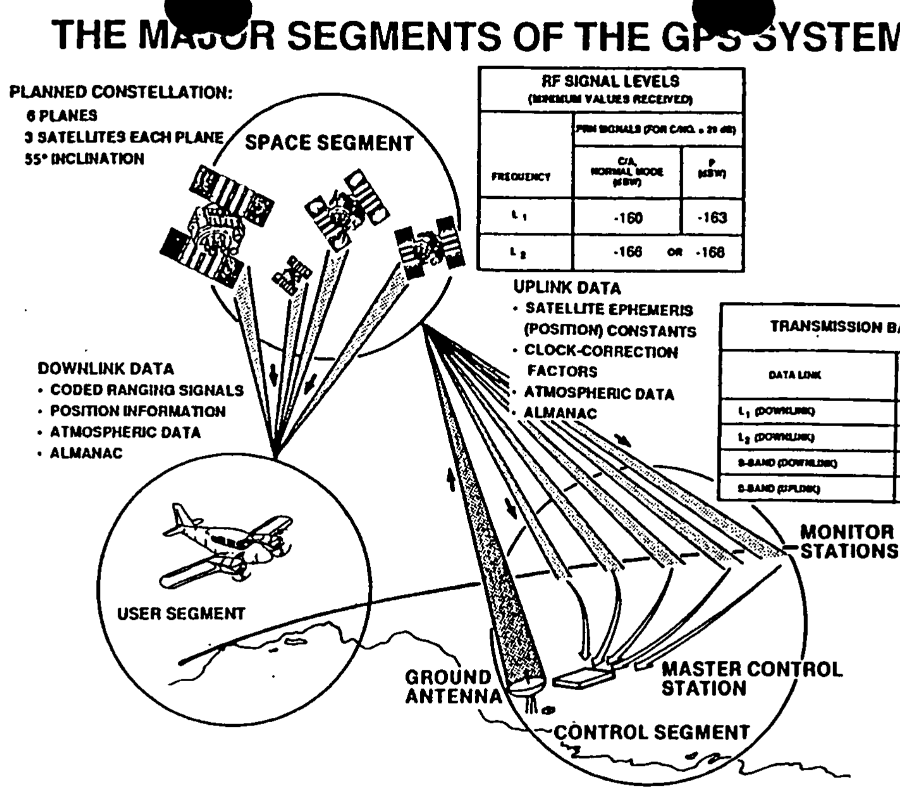


Figure 2.1. The Navstar Global Positioning System can be broken into three major pieces or segments: the *space segment*, which consists of 21 Navstar satellites plus 3 active on-orbit spares, the *user segment*, which consists of tens of thousands of military and civilian receivers, and the *control segment*, which consists of five unmanned monitor stations, a master control station, and a set of ground antennas installed at widely separated locations around the globe.

the four ground antennas that transmit fresh ephemeris coordinates and clock correction factors to the satellites for rebroadcast back down to the users on or near the ground.

The Space Segment

The purpose of the space segment is to furnish accurate timing pulses and satellite ephemeris constants to a worldwide class of users who need to fix their positions, velocities, and/or the exact time. The ephemeris consists of 16 constants that are broadcast to the Navstar receivers so that they can determine where each satellite was when it transmitted its timing pulses. Figure 2.2 depicts the relative locations of the 24 satellites in the Navstar

THE NAVSTAR CONSTELLATION

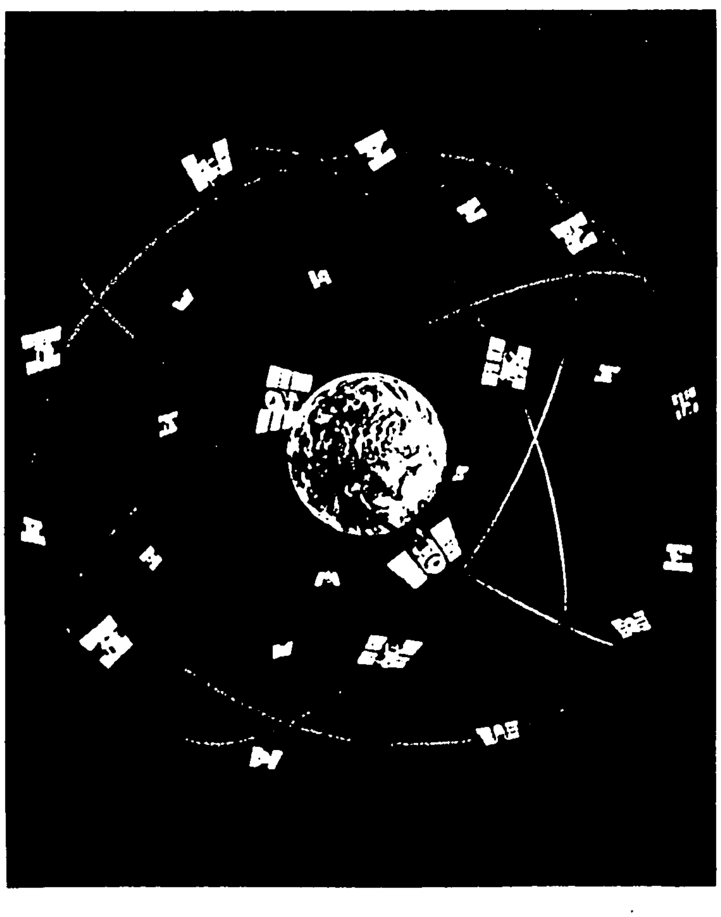


Figure 2.2. The fully operational GPS constellation consists of 21 Navstar satellites plus 3 active on-orbit spares traveling around 12-hour circular orbits 10,898 nautical miles above the globe. One feedback control loop helps maintain a continous earth-seeking orientation for 12 navigation antennas on the main body of the spacecraft, and another helps maintain a similar sun-seeking orientation for its two winglike solar arrays.

constellation at a particular instant in time. Notice that, due to perspective, the satellites in the background appear to be smaller than the ones that are closer to the viewer. The winglike solar arrays protruding from the two sides of each spacecraft are always tilted with the proper orientation to catch the perpendicular rays of the sun. The navigation antennas, which are affixed to the lower edge of the spacecraft, always point toward the earth.

Signal Structure and Pseudorandom Codes

To determine its position, a Navstar receiver measures the signal travel times associated with the binary pulse trains from four or more of the satellites. The signal travel time multiplied by the speed of light (186,000 miles per second) equals the slant range from the satellite to the user. By measuring the instantaneous Doppler shift associated with those same four satellites, the receiver can also determine its three mutually orthogonal velocity components.

All of the carrier waves streaming down from the satellites are right-hand circular polarized. This is accomplished by using 12 spiral-wound helical antennas arranged in a tight pattern. Four of them are located in the center quad. The other eight are arranged in a circular ring surrounding the center quad. Circular polarization allows the user-set antennas to access the faint satellite signals without boresight pointing.

Every satellite in the Navstar constellation transmits continuously on the same two L-band frequencies. The reciever uses code-division multiple access to distinguish the satellites from one another. Two different binary codes, the C/A-code and the P-code, are superimposed on the two L-band carrier waves emanating from each satellite. The C/A-code (*Coarse Acquisition Code*) is available free of charge to civilian users all around the world. The P-code (*Precision Code*) is reserved for high-precision military users. It is protected through encryption techniques that restrict access and deny full accuracy to unauthorized users.

Each of the satellites in the Navstar constellation is assigned its own unique C/A-code and its own unique P-code. The C/A-code has a chipping rate of 1 million bits per second, with a repetition interval of 1,023 bits. Thus, it repeats after approximately one one-thousandth of a second. The P-Code has a chipping rate of 10 million bits per second. Its repetition interval is approximately 6×10^{12} bits. Seven days elapse before the P-code sequence repeats. Both the C/A- and the P-codes are pseudorandom binary pulse sequences, with a high degree of "randomness" in their binary 1s and 0s. The "randomness" is only apparent. Actually, the binary pulses are generated by precise mathematical relationships with total predictability.

Phase-shift-key modulation is used to mark the interfaces between the binary 1s and the binary 0s. This means that the L_1 and the L_2 carrier waves experience sharp mirror-image reflections whenever the C/A-code or the P-code switches from a binary 1 to a binary 0 or vice versa. An opportunity for an instantaneous phase shift occurs every one-millionth of a second for the C/A-code and every ten-millionth of a second for the P-code. The L_1 frequency carries both the C/A-code and the P-code transmitted in phase quadrature. This means that they are always 90 degrees out of phase to one another. The L_2 carrier wave is modulated with the military P-code only.

Navigation Solutions

If the Navstar satellites all broadcast on the same two frequencies, how can a Navstar receiver distinguish between the various satellites in the constellation? This is accomplished by code-division multiple access. Each Navstar satellite is assigned its own unique C/A-code and its own unique P-code. Real-time code-matching techniques are used to distinguish among the various satellites and to measure the appropriate signal travel time.

Consider satellite number 1, which is transmitting its own unique C/A-code down toward the users on the ground, as shown in Figure 2.3. This pulse train reaches the ground in approximately one-eleventh of a second or less. The Navstar receiver generates an identical C/A-code pulse train, but it is shifted (displaced) with respect to the pulse train coming down from the satellite.

In order to bring the two identical pulse trains into correspondence, the receiver automatically slews (gradually shifts) the one it is generating. When the two binary pulse trains have been brought into correspondence, binary 1s from the receiver are matched against binary 1s from the satellite, and binary 0s are matched against binary 0s. When coincidence occurs, the *auto-correlation function* suddenly jumps from a value of 0 to a value of 1. This is called "lock-on."

Once lock-on has been successfully achieved, the user set can measure the signal travel time plus or minus the timing error in its quartz crystal oscillator. Fortunately, the magnitude of this so-called "clock-bias error" is the same for each satellite in the constellation. Thus, by measuring the time delays for four or more satellites, the user set can set up a system of four equations in four unknowns to mathematically eliminate the clock-bias error. The four equations used in determining the user-set position are presented at the bottom of Figure 2.3. The four unknowns are U_x, U_y, and U_z (the user's three mutually orthogonal position coordinates) and C_B (the clock bias error in the user-set clock).

These equations cannot be solved explicitly for the four unknown variables, but, of course, they can be solved iteratively using Taylor series expansions. The subscripted variables X_1, Y_1, Z_1 in the first equation are the instantaneous position coordinates of the first Navstar satellite at the time that its timing pulses were transmitted. The user set computes the values of X_1, Y_1, and Z_1 by substituting the ephemeris coordinates streaming down from the first satellite into a set of simple algebraic and trigonometric equations. These precise solutions also require numerical interation.

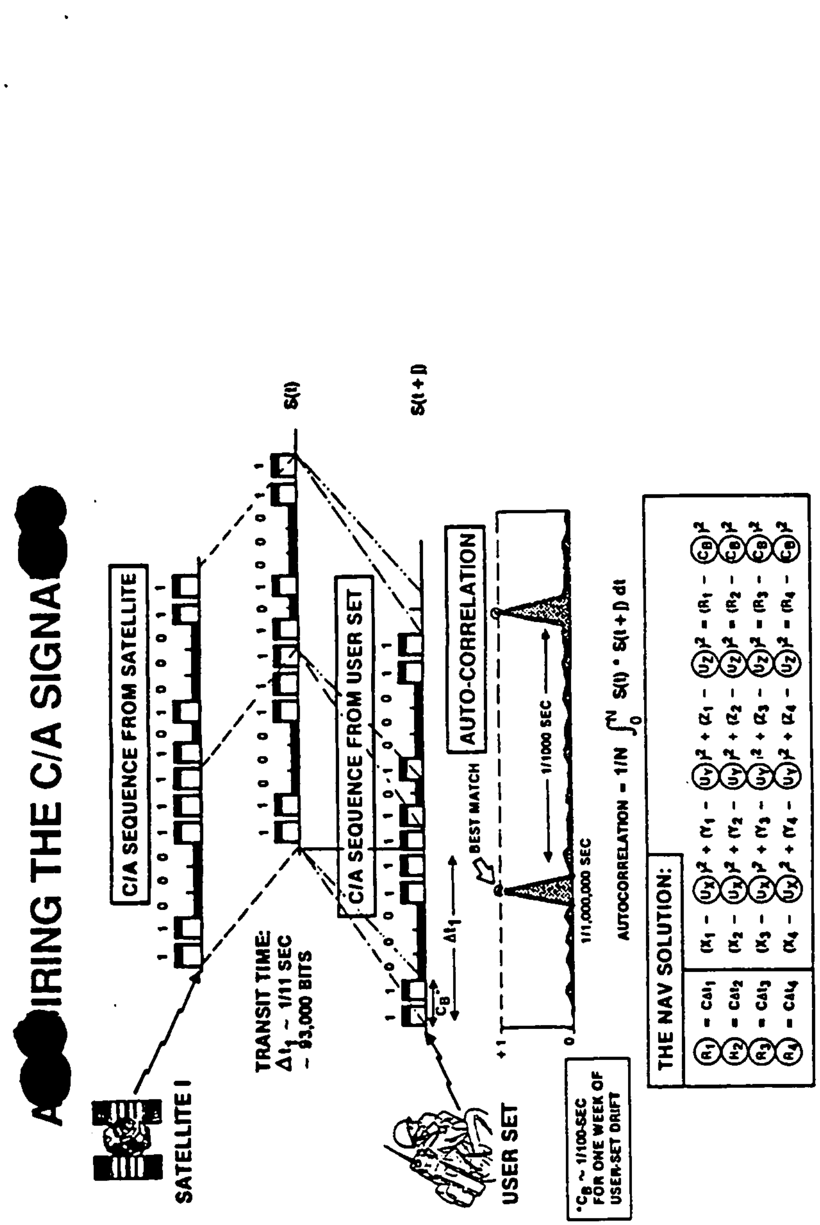


Figure 2.3. Each Navstar satellite transmits two spread-spectrum binary pulse trains, copies of which are created in real time by the user-set electronics. An automatic feedback control loop in the user set stews its pulse train to bring it into correspondence with the identical pulse train being braodcast by the satellite. When correspondence is achieved, the user set can establish the signal travel time plus or minus the clock bias error $\leq_B$. This procedure is repeated for at least three other satellites, to obtain the timing measurements necessary to determine the user's three position coordinates u_x, u_y, and u_z.

Navigating Lightning Strikes

Most radionavigation systems determine a navigator's position by measuring the signal travel time of one or more electromagnetic signals. You can use a similar technique to determine the approximate range to an unexpected lightning strike.

First, watch for the flash of lightning. Then count the number of seconds until you hear the sound of thunder. For every five seconds separating lightning flash from thunder sound, there is a one-mile distance between your body and the place where the lightning singed the ground. This simple ranging measurement is based on the fact that the visible light from the lightning flash reaches your eye almost instantly, but the thunder-sound ambles along through the air at only about 1000 feet per second.

How can you refine this primitive "navigation" technique to pinpoint the longitude and latitude of an unexpected lightning strike? One fruitful approach is to send two ground-based observers to widely separated locations. When a lightning strike occurs, each observer counts off the number of seconds until he hears the rumbling sound of thunder. This establishes two circular lines of position, each centered at one of the observer's locations.

In general, the circles will intersect at two different points, one of which corresponds to the location where the lightning bolt touched the ground. Is there any easy way to resolve the solution ambiguity? How about visiting each of the two intersection points to see whether a lightning-damaged tree might be smouldering there?

Thus, we see that the fundamental solution algorithm for the Navstar system is amazingly simple. However, in practice, a number of complicating factors quickly arise. In particular, corrections for three major types of time delays are required:

1. Relativistic time delays
2. Ionospheric distortion
3. Tropospheric distortion

Correcting for Relativistic Time Delays

The relativistic time delays arises in accordance with Einstein's general and special theories of relativity. The clock on board a Navstar satellite ticks at a different rate than the clock in a receiver because the satellites are in a different strength gravitational field and because they are moving at a different velocity than the clock in the Navstar receiver. The pull of the earth's gravity at the GPS altitude is only about 6 percent as strong as the pull of gravity on a receiver on the surface of the earth. The satellite velocity is approximately 12,000 feet per second, compared with 1,000 feet per second or less for the clock in a typical GPS receiver.

Of course, the engineers who design the Navstar system know in advance that, when the satellites are launched into space, they will be in an environment where Einstein's relativistic time-dilation effects will arise with predictable magnitudes. So they instruct the manufacturer to purposely offset the ticking rates of the satellite clocks, to compensate for the relativistic effects they know will later occur.

If the GPS satellites could be launched into perfectly circular orbits, offsetting the ticking rates of their clocks would compensate for virtually all of the relativistic time dilation. Unfortunately, in practice, the orbits of the satellites will always be slightly eccentric. The maximum tolerance in eccentricity for the Navstar orbits is 2 percent. This means that, at their perigee (point of closest approach to the earth), the satellites can be, at most, 288 nautical miles closer to the earth's center than they are at apogee (furthest point from the earth).

As a GPS satellite travels around its elliptical (egg-shaped) orbit, it experiences a sinusoidal variation in relativistic time dilation. As it falls down from apogee toward its perigee, it passes into a stronger gravitational field and its orbital speed increases. This causes the ticking rate of its onboard clock to change with respect to the clock installed in a Navstar receiver on or near the ground. During each 12-hour orbit, the variation in the ticking rate of its clock amounts to, at most, 46 nano seconds (assuming the maximum 2-percent eccentricity).

This time dilation is easily removed by the computer in the Navstar receiver, which substitutes the satellite's known orbital elements into a simple system of closed-form equations. Incidentally, if the Navstar satellites could be launched into perfectly circular orbits 1,800 nautical miles above the earth, the relativistic effects due to the general theory of relativity and the special theory of relativity would nullify one another and no relativistic corrections would be required. However, the earth coverage characteristics at that altitude are not favorable, so a larger constellation would be required.

The relativistic time dilation effects for Navstar navigation are surprisingly large. If the ticking rate of each clock was not offset during manufacture, a typical navigation error after 24 hours without ground updates would amount to approximately 18 nautical miles! The effects due to orbital eccentricity would amount to 100 feet or less.

Correcting for Ionospheric and Tropospheric Delays

When the signals from the Navstar satellites pass through the earth's ionosphere, they are bent and slowed down slightly. The resulting time delay is inversely proportional to the square of the transmission frequency, so two transmission frequencies (L_1 and L_2) can be used to compensate. Each frequency results in a slightly different time delay. Consequently, a simple mathematical correction can be programmed into the sophisticated P-code receivers to extract out nearly all of the ionospheric delay.

The simpler C/A-code receivers pick up only the L_1 signal, so they cannot extract out the ionospheric delay using dual-frequency compensation techniques. Instead, the C/A-code receivers mathematically model the current behavior of the earth's ionosphere, using a set of polynomial coefficients that are included in the satellite's 50-bit-per-second data stream. These coefficients enable the receiver to reduce the ionospheric error by approximately 50 percent, compared with an uncorrected solution. This is usually sufficient for most C/A-code civilian applications.

The tropospheric time delay arises because, when the signals from the Navstar satellite pass through the earth's atmosphere, they are slowed down slightly. The tropospheric delay is quite a bit larger when a satellite is situated near the horizon because its signals pass through a thicker portion of the earth's atmosphere. The time delay is also larger when the Navstar receiver is near the surface of the earth as opposed to being at a higher altitude. The simplest mathematical correction for the tropospheric time delay is a negative exponential function of altitude and a cosecant function of the elevation angle above the local horizon. For demanding applications, more complicated mathematical models are frequently used.

Decoding the 50-Bit-Per-Second Data Stream

A 50-bit-per-second data stream (see Figure 2.4) is superimposed on the C/A-code and the P-code pulse trains coming down from the Navstar

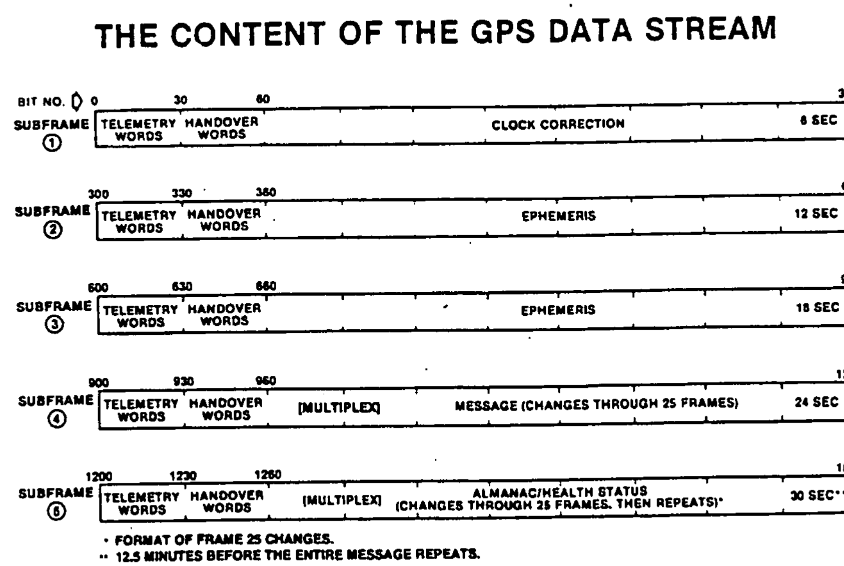


Figure 2.4. The 50-bit-per-second data stream transmitted by each Navstar satellite is superimposed on the pseudorandom C/A- and P-code pulse trains by means of modulo 2 addition. The 30-second frames are further subdivided into five subframes, each of which lasts 6 seconds and contains 300 bits of information. The clock correction factors and the ephemeris constants located in subframes 1 and 2 help the receiver measure the pseudorange to each satellite so that the receiver can accurately establish its three-dimensional postion coordinates.

satellites. This 50-bit-per-second data stream includes the latest information on the behavior of the satellite clocks and the latest values for their orbital elements (ephemeris constants). The data stream also includes special messages defining the current signal strengths and other health status information for the satellites. This information is frequently updated by the control segment on the ground.

The 50-bit-per-second data stream is divided into 30-second frames, each of which contains 1,500 bits of information. Each frame is divided into five 6-second subframes, each containing 300 bits. Subframe 1 contains the four clock-correction factors, defining the current errors and error growth rates for the satellite clock. Subframes 2 and 3 contain ephemeris constants, defining the current orbit of the satellite.

Subframe 4 contains navigation messages and satellite health status information. Subframe 5 contains the constellation almanac. The almanac is similar to the ephemeris, but there are certain key differences. The almanac contains fewer constants and, consequently, defines a less accurate orbit than the ephemeris. Moreover, the almanac being broadcast by each Navstar satellite defines the orbits to all of the operational satellites in the Navstar constellation.

In each successive 30-second frame the almanac for a different satellite is contained in Subframe 5. Thus, over a transmission interval of about 12 minutes, each satellite tells the users where all the other satellites in the constellation are located in space. The almanac information is not used directly for pseudo-ranging navigation. Instead, it is used in determining which satellites are currently above the horizon and which four are most favorably located to provide the smallest error in the navigation solution.

The 50-bit-per-second data stream is superimposed on the C/A- and the P-code pulse trains using modulo-2 addition. In the modulo-2 addition table:

$$0 + 0 = 0$$
$$1 + 0 = 1$$
$$0 + 1 = 1$$
$$1 + 1 = 0$$

Thus, whenever a binary 1 occurs in the 50-bit-per-second data stream, the modulo-2 addition "inverts" 20,000 adjacent binary digits in the 1 million-bit-per-second C/A-code. Binary 1s become binary 0s and vice versa. A binary 0 in the 50-bit-per-second data stream leaves 20,000 adjacent C/A-code bits uninverted (the same as they were before).

The Various Families of Navstar Satellites

The Navstar satellites can be divided into major families having similar physical characteristics. The initial Block I satellites produced by Rockwell International each weighed approximately 960 pounds and generated 420 watts end-of-life electrical power. With one exception, all 11 of the Block I satellites reached orbit successfully and all of them operated approximately 3 years or more. Some were still functioning 13 years after launch. The Atlas F booster that was carrying Navstar 7 into space exploded over Vandenberg Air Force Base shortly after liftoff. Each Block I satellite is constructed from 35,000 separate parts. But, when its booster explodes, an even larger number of parts are created. Consequently, no attempt is being made to reassemble Navstar 7.

Navstar 12 was a Block II qualification unit, never intended for flight. The 28 Block II satellites, also produced by Rockwell International, weigh approximately 2,000 pounds each and generate 700 watts end-of-life electrical power. The Block II satellites were originally designed for launch aboard the Space Shuttle, but when the Shuttle Challenger disaster occurred in 1988, they were reassigned to the Delta II expendable booster (medium launch vehicle). All of the Block II satellites launched so far have reached orbit successfully. So far, none have failed.

The 20 Block IIR (replenishment) satellites weigh about 2,300 pounds and generate 1,000 watts end-of-life electrical power. They are produced by General Electric. The Block IIR satellites are scheduled for launch in the mid-1990s.

The User Segment

The purpose of the user segment is to process the time and position information from four or more satellites (either simultaneously or sequentially), to obtain accurate position, velocity, and timing measurements. A Navstar receiver can be divided into three major components: the antenna with its associated electronics, the receiver-processor unit, which picks up the satellite signals and performs the navigation solution, and the control-display unit, which provides information display and a convenient interface between the user and the Navstar system.

A Typical High-Performance 5-Channel Receiver

Multichannel receivers such as the one sketched in Figure 2.5 often serve high-dynamics users, such as military jets. Each separate channel is a radio receiver (front end) that locks on to a separate satellite and tracks it continuously to obtain its instantaneous pseudo-range and its instantaneous Doppler shift. A military avionics receiver of this type often employs two antennas. One is mounted on the top of the aircraft, the other is mounted on its belly. Thus, the receiver can achieve continuous signal reception, even when the aircraft is flying upside down.

A TYPICAL FIVE-CHANNEL USER SET

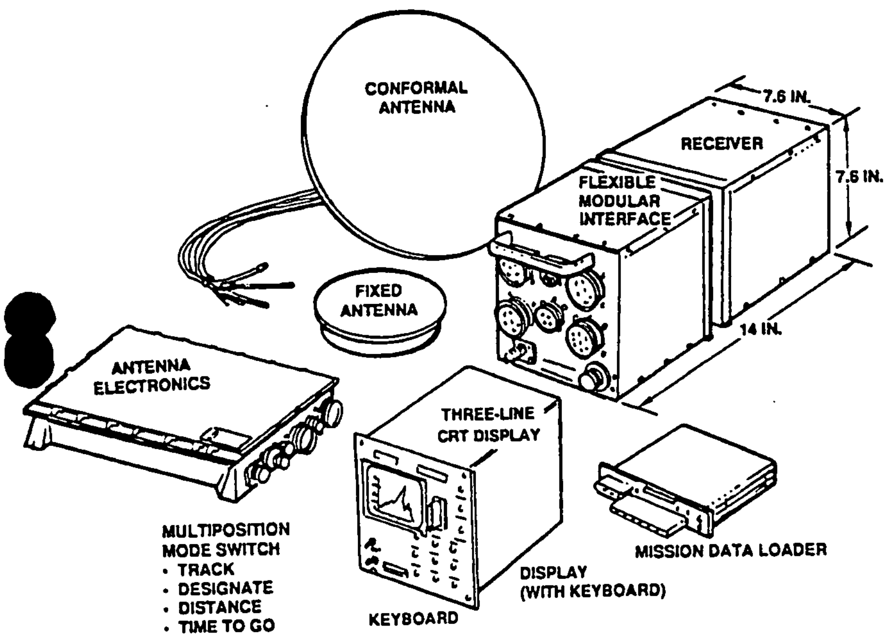


Figure 2.5. Some high-performance military receivers pick up navigation signals from two different antennas mounted on the top and the bottom of the aircraft fuselage. This allows the receiver to gain access to the navigation signals, even when the aircraft is flying upside down. Signals from the active antenna are routed through the antenna electronics to the receiver, which handles the navigation solution. The receiver then feeds the results through the flexible modular interface to the control display unit, where it is presented on the screen convenient pictorial or alphanumeric format.

After signal conditioning and amplification, the modulated signals from the appropriate antenna are routed into the receiver unit, which uses computer processing techniques to carry out the navigation solution. This information is, in turn, fed to the control display unit, which usually includes either a liquid crystal display or a cathode ray tube (CRT) screen with a simple keyboard and an (optional) multiposition switch. The control display unit allows the operator to feed in information and to operate the unit in different navigational modes.

The three-dimensional position coordinates, provided by a military P-code receiver, are required to be accurate to within 50 feet SEP (spherical error probable). Such a receiver also provides three mutually orthogonal velocity components with an average accuracy of about 0.3 feet per second.

The velocity components U_x, U_y, and U_z are determined by measuring the instantaneous Doppler shift.

The navigation accuracy available to a particular Navstar user depends on two separate factors:

1. The average User-Equivalent Range Error (UERE) along the line-of-sight vector connecting the user to each satellite.
2. The instantaneous Geometrical Dilution of Precision (GDOP), which defines the geometry of the best four satellites as seen from the user's position on or near the earth.

The 1σ navigation error, which is typically 50 feet or less, is approximately equal to the product of these two quantities (UERE times GDOP).

The largest error component in the User-Equivalent Range Error is caused by clock instabilities and unmodeled space perturbations, which are dominated by the uncertainties in the solar radiation pressure pushing on the spacecraft. Other smaller errors include modeling uncertainties in the satellite ephemeris coordinates and small unmodeled time delays experienced by the electromagnetic signals as they travel through the ionosphere and troposphere. Surprisingly, the overall User-Equivalent Range Error arising from the statistical combination (root-sum-square) of all these different error sources amounts to only about 18 feet when daily control segment updates are routinely achieved. The global time average for the Navstar's GDOP is about 2.3 for a 24-satellite GPS constellation. The product of the average UERE times the GDOP yields an average three-dimensional navigation error for the high-precision military users of only about 50 feet.

The Navstar navigation system provides even smaller errors when it is used for differential navigation. In the differential navigation mode two different receivers pick up the signals from the same four Navstar satellites and exchange information relating to their current navigation solutions. Many of the error components are common to the two solutions, and, consequently, the resulting positioning error is considerably smaller. Depending on the method of implementation, differential navigation errors as small as 6 feet or even less are often achieved.

Operating Procedures

When a Navstar receiver is installed aboard a high-performance military aircraft, its displays are similar to the ones provided by inertial navigation systems, which military aviators have been using for many years. The navigator can typically enter up to 200 waypoints. A waypoint is an intermediate longitude-latitude combination that the airplane must fly through in order to reach its final destination. High-performance military jets are also equipped to process and display moving waypoints and stationary mark

points. A *moving waypoint* enables the pilot to rendezvous with another aircraft at or near a specific location. A *markpoint* is a longitude-latitude combination that the pilot needs to mark for future reference. At the push of a button the markpoint is stored in the user set's electronic memory. On a future mission it can be converted into a waypoint to vector the aircraft to the location the pilot marked.

Generally speaking, whenever a GPS receiver is turned on, it automatically provides an accurate navigation solution without manual inputs or human intervention. When it is turned off, it stores its last position coordinates in a nonvolatile electronic memory. When it is turned on again, these coordinates become its estimated position. The nonvolatile memory also stores the last set of almanac constants, defining the locations of all the functioning satellites in the current constellation. These constants are used in the new navigation solution to determine which satellites are above the horizon and which four are the most favorably located to provide an accurate position fix. Even when the user set is turned off, its quartz crystal clock continues to operate. That clock provides the necessary time estimate when the set is later reactivated to obtain a new navigation solution.

The Control Segment

The purpose of the control segment (see Figure 2.6) is to track the GPS satellites and provide them with periodic updates, correcting their ephemeris constants and their clock-bias errors. When the Navstar system was being designed, some of the project engineers proposed tracking the satellites with ground-based lasers reflected from satellite-mounted corner-cube reflectors. However, since the satellites are always transmitting information relating to their current locations, ground-based facilities can be used to *invert* the navigation solution to obtain the desired satellite positioning information.

Inverting the Navigation Solution

A Navstar navigation solution is normally obtained by picking up the C/A- or P-code signals from four or more satellites scattered across the sky. The control segment, in effect, turns the navigation solution upside down. This is accomplished by installing a set of unmanned monitor stations at widely separated locations on the ground. Four monitor stations pick up the navigation signals from a particular satellite at the same time. The monitor stations are independently surveyed to fix their positions, and they are equipped with synchronized cesium atomic clocks to nail down the time to a high degree of precision. The four pseudo-range measurements are then used in an *inverted* navigation solution to fix the location of the satellite and to determine the timing errors in its onboard atomic clock.

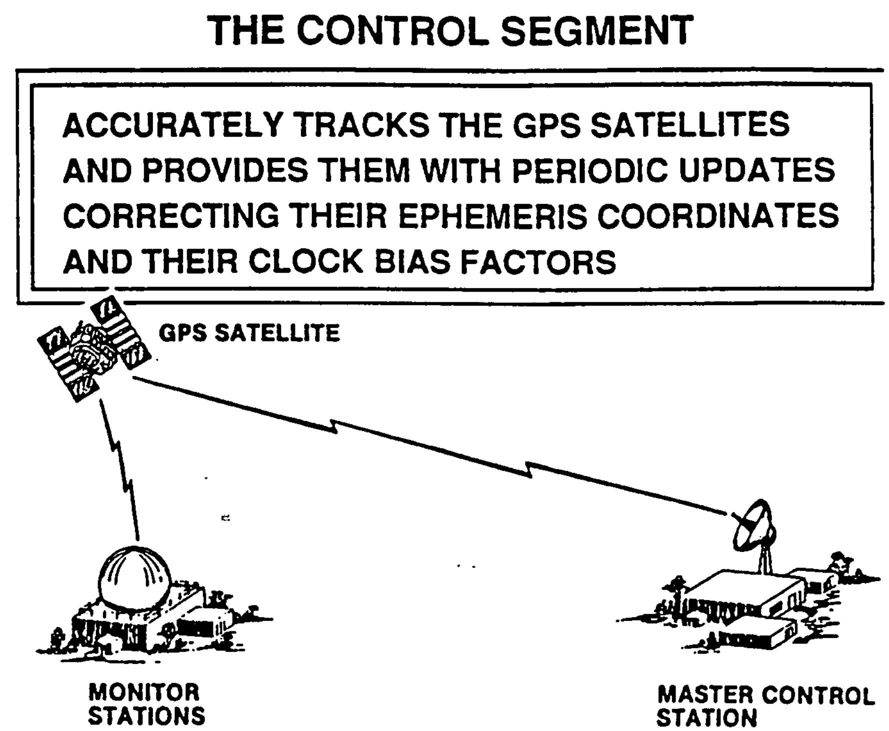


Figure 2.6. Unmanned monitor stations at widely separated locations pick up the signals from each Navstar satellite as it sweeps across the sky. The resulting pseudo-range measurements are then transmitted to the master control station, where they are computer-processed to establish the satellite's clock correction factors and its current orbital elements. These parameters are transmitted to each satellite at least once per day from the four ground antennas positioned around the globe.

In actual practice, hundreds of extra pseudo-range measurements are obtained and used in an overdetermined least-squares solution to improve the accuracy of satellite's ephemeris constants. All of the pseudo-range measurements to each satellite are recorded on wideband tape recordings. These measurements are later transmitted to the master control station, a computer processing facility operated by the U.S. Air Force called the Consolidated Space Operations Center (CSOC). CSOC, which services many military satellites, is located in a secure enclave in Colorado.

The master control station computer-processes the complete collection of pseudo-range measurements to determine the ephemeris coordinates of each satellite and the errors in its onboard atomic clock. This information is then relayed to each satellite once per day on S-band from various 16-foot ground antennas positioned around the globe.

The Monitor Stations and The Master Control Station

Five unmanned monitor stations serve the GPS Block II constellation. They are located at Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs, Colorado. The Master Control Station is located at CSOC in Colorado Springs. The ground antennas used in uploading the satellites are located at Ascension Island, Diego Cargia, and Kwajalein, with a backup shared for other purposes at Colorado Springs.

Field Test Results

Hundreds of realistic field tests conducted by military personnel at Yuma, Arizona, and at other military installations throughout the world have helped to reveal the actual operating characteristics of the Navstar Navigation System. Signal strength and navigation accuracy tests, for example, were vitally important to early mission planners. Ever since they were first installed, the Navstar satellites have been blanketing the earth with surprisingly strong navigation signals. Generally speaking, the signal strength received on the ground has been three to four decibels above the required military specifications. At any given moment, each Navstar satellite blankets 42 percent of the globe with nearly constant-intensity radio frequency transmissions. The maximum signal strength does not occur when a satellite is directly overhead, but rather when it is approximately 40 degrees above the horizon. This stems from the shaped-beam characteristics of the RF signals that originate from the satellite's 12-element helical antenna array.

Early static positioning tests using signals from the Navstar satellites demonstrated highly accurate positioning solutions. Military performance specifications called for a 50-foot average navigation error, but even the early tests provided root-mean-square navigation errors of approximately 24 feet. More recent military tests have yielded similar results even though, on the average, the ground updates have usually been at least several hours older when more recent tests were conducted.

Aerial rendezvous tests using Navstar navigation signals have also demonstrated surprisingly accurate results. In six independent rendezvous tests between an F-4 aircraft and a C-141 military tanker, for instance, the maximum miss-distance between the centerlines of the two airplanes was only about 100 feet. Thus, the biggest centerline miss-distance was only slightly larger than the wing span of the C-141.

Early landing approach tests also provided test engineers with some rather encouraging results. In six independent landing approach tests the C-141 remained well within the boundaries of the instrumented landing system in both azimuth and elevation. The Navstar system thus provided accuracies comparable to existing ground-based landing systems used for landing approach operations.

In early harbor navigation tests in which a fast frigate sailed under the Del Coronado Bridge in the San Diego Harbor, the navigation officers found that some of the buoys marking the boundaries of the safe harbor channel were displaced from their intended locations by as much as 100 feet. Simulated fog increased the difficulty of this early navigation test, but nevertheless the departure trajectory of the fast frigate closely approximated the trajectory it would have followed with ideal viewing conditions under visual navigation control.

3

Performance Comparisons for Today's Radionavigation Systems

Simple radionavigation systems first began to flourish high above the smoke-powder killing fields of World War II. During that conflict, digital pulse trains and serpentine carrier waves guided both Allied and Axis bombers over land and sea. Later, when peace descended on the European continent, derivative ground-based navigation systems helped foster many useful civilian and military applications.

In the late 1950s, when instrument-laden payloads began popping up into outer space, satellite-based transmitters supplemented and replaced the big, spider-beam antennas poking up from the ground. In this chapter we will review the salient characteristics of several representative ground-based and space-based radionavigation systems, and we will compare them with one another on the basis of coverage areas, accuracy levels, transmission frequencies, and the like.

A Sampling of Today's Ground-based Navigation Systems

Far from the rumbling battlefields of World War II, both German and British scientists were highly motivated to develop simple but effective radionavigation systems to help improve the accuracy of bomb delivery techniques. Some World War II systems, such as Decca, are still being used today, although modern refinements have made them more practical and accurate. Others are based on the fundamental architectures of these early World War II systems.

Loran C/D

Loran was one of the earliest and most successful systems for ground-based radionavigation.[1] Two versions are currently in operation: Loran C, which serves civilian users, and Loran D, which serves the military. Often, the transmitters for the two versions of Loran are co-located, especially in the United States.

In its original design, Loran employed time-difference-of-arrival techniques, with the ground-based transmitters working together in pairs to position the user along a hyperbolic line of position on the surface of the earth. The two transmitters, which are today referred to as the *primary* and the *secondary*, are usually separated by a few hundred miles. The secondary transmitter monitors the modulated signals being broadcast by the primary transmitter in order to maintain mutual time synchronization.

A Loran receiver measures the time-difference-of-arrival of the two signals to fix its location on a hyperbolic line of position. By performing similar measurements using the signals from two other Loran transmitters, the receiver can fix its longitude and latitude on the spherical earth.

Loran's carrier waves are transmitted at approximately 100 kilohertz, with wavelengths that are around 1.6 miles long. Thus, the navigation solutions provided by Loran are not particularly accurate. Its ground waves provide coverage over a range of about 1,800 miles with a two-dimensional error amounting to 1,500 feet (at the 95-percent probability level). Sky-wave navigation extends the coverage regime to 2,500 miles, but the signals from the transmitters then reflect off the ionosphere and the positioning error increases to 6,000 to 12,000 feet.

Chains of Loran transmitters cover most of the heavily traveled coastal areas in the Northern Hemisphere. More than 50 transmitters are currently in operation, but all together they provide coverage for only about 10 percent of the globe. At an estimated cost of $60 million, a new mid-continent chain of Loran transmitters is being installed in the midwestern United States. These new transmitters, together with their predecessors, will provide essentially continuous coverage from coast to coast in the lower 48 states.

Omega

Like Loran, Omega was originally designed as a hyperbolic radionavigation system, but it employs phase-difference-of-arrival rather than time-difference-of-arrival techniques to fix the user's position. The Omega system includes only eight very-low-frequency transmitters, but it provides essentially global coverage. On the average, the Omega transmissions cover 88 percent of the globe by day, 98 percent by night. Broader coverage is

[1]Loran stands for Long Range Area Navigation

achieved on the nighttime side of the earth because the ionosphere rises in height when nightfall comes and, hence, Omega's reflected signals span a broader coverage area. Although Omega achieves broad area coverage with only eight transmitters, its 2σ navigation error is quite large: 2 to 4 nautical miles. The transmitters operate in the 10 to 13 kilohertz range, with carrier waves that are approximately 16 miles long.

When it is operated in the *differential navigation mode,* Omega's accuracy improves to 1,000 to 2,000 feet. In the differential navigation mode, two or more radionavigation transmitters exchange information with one another, so many of the positioning errors common to the two solutions can be eliminated. In this case, of course, its positioning solutions are measured with respect to the differential base station.

VOR/DME Tacan

VOR/DME Tacan is sued in vectoring civil and military airplanes from one navigation beacon to another along heavily traveled airline routes.[2] The operational characteristics of the VOR portion of the system are sketched in the upper left-hand corner of Figure 3.1. Notice that it employs two different types of signals working together in partnership: a narrow-beam rotating "lighthouse" transmission coupled with a "blinking" omnidirectional pulse. The lighthouse beam rotates at a constant rate of 30 revolutions per second as it systematically circles around the points of the compass. When the rotating beam is pointing toward the North Pole, the blinking signal is briefly broadcast in all directions. Thus, an airplane that is vectoring itself straight toward the transmitter always experiences the same time delay between the receipt of the omnidirectional pulse and the rotating narrow-beam signal. If, for instance, the approach is along a 240-degree azimuth, the airplane will always observe a time delay of one forty-fifth of a second between the receipt of the two different kinds of signals.

The DME portion of the VOR/DME system uses two-way active spherical ranging to measure the slant range between an aircraft and the transmitting station. The avionics system on board the aircraft transmits an interrogation signal toward the DME station, which it immediately rebroadcasts on a different frequency. The slant range to the transmitting station is then obtained by multiplying half the total signal travel time by the speed of light. The operation of the military Tacan portion of this system is similar to the civilian VOR/DME, but it achieves improved accuracies by transmitting at higher pulse rates with higher frequency carrier waves.

The 2σ navigation error for VOR/DME Tacan is approximately 200 to 600 feet. Note, however, that this is actually an angle-measuring system, with an average pointing error of approximately 3 degrees. Consequently, as an

[2]VOR = VHF Omnidirectional Range; DME = Distance Measurement Equipment.

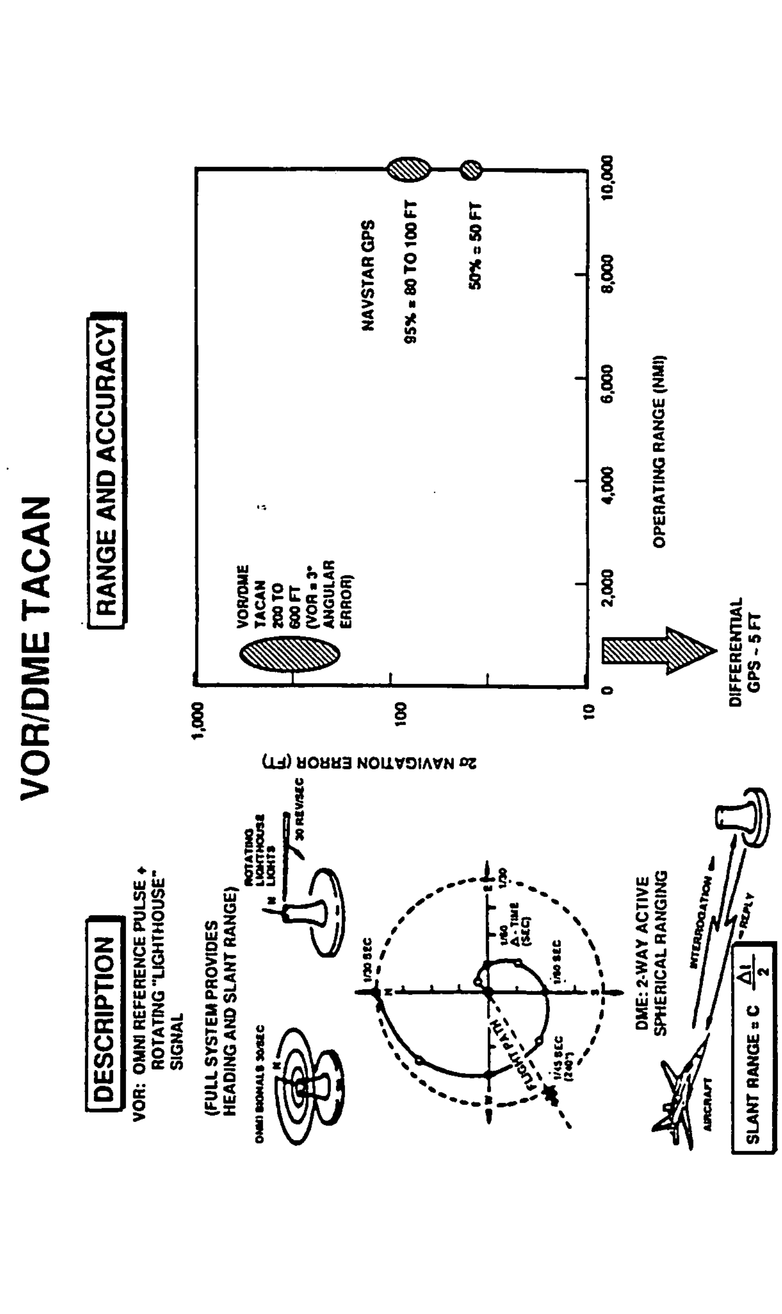


Figure 3.1 Thousands of pilots and navigators vector airplanes, large and small, from waypoint to waypoint using the signals from VOR/DME. The receiver on an airplane determines the proper bearing to a particular transmitter by noting the difference in the arrival times between the blinking omnidirectional signal and the rapidly rotating narrow-beam lighthouse signal. The instantaneous slant-range to the transmitter is determined separately by two-way active spherical ranging.

airplane gets closer and closer to the transmitter, its positioning error systematically decreases.

The Federal Aviation Administration and The Department of Defense operate more than 900 domestic VOR/DME Tacan transmitters, with skimpier coverage being provided throughout the rest of the world. Transmission frequencies range from 108 to 118 megahertz for the VOR portion of the system, and 960 to 1,215 megahertz for the Tacan portion. The corresponding carrier waves are only a few feet long, so, over its relatively short operating ranges, the system can be surprisingly accurate. However, its carrier waves punch through the earth's ionosphere, so only local line-of-sight coverage is achieved.

The Microwave Landing System

The Microwave Landing System (MLS) is used in landing properly equipped airplanes and helicopters at local airports throughout the Western world. The MLS is gradually replacing the ILS (Instrumented Landing System), a simpler radionavigation system that provides airplanes with a localizer pattern (fixed azimuth angle) and a glide-slope pattern (fixed angle of descent). The ILS localizer pattern aligns the airplane's flight path with the airport runway. The glide-slope pattern provides it with the proper sloping line of angular descent. "Marker beacons" at three discrete distances from the end of the runway pinpoint the location of the aircraft with respect to its intended touchdown point. The accuracy of the Instrumented Landing System is approximately 15 to 30 feet. However, ILS is an angular system with an average angular error of 0.05 degrees so that, when the airplane gets closer to its touchdown point, its positioning error systematically declines.

The Microwave Landing System (MLS) uses "windshield wiper" transmissions to help direct aircraft landing operations. One of the two modulated beams sweeps back and forth horizontally to provide the airplane with the proper elevation angle for its gradual descent.

The Microwave Landing System provides roughly the same accuracy as the Instrumented Landing System, but its unique signal structure and its cleverly designed beam manipulation techniques allow pilots to approach the runway along curved or segmented trajectories. This additional flexibility is useful for noise abatement and for landing operations involving helicopters and short-takeoff-and-landing aircraft. NASA's Shuttle Orbiter also uses the Microwave Landing System at Cape Kennedy, Florida, and at Edwards Air Force Base in California, when it touches down on the ground like a butterfly with sore feet.

The Microwave Landing System operates over a range of 17 to 35 miles. Approximately half of all the airplanes licensed for operation in the United States are equipped to pick up the signals being broadcast by the Instrumented Landing System. More than 700 ILS facilities are currently in operation at American airports they service a total of 120,000 users, mostly

small private planes. The more advanced MLS system is being developed jointly by the Department of Transportation, the Department of Defense, and the National Aeronautics and Space Administration. Present plans call for the installation of MLS transmitting equipment at 1,250 American airports, but current installations have been falling behind schedule.

The carrier waves for the Instrumented Landing System are centered at 110 and 330 megahertz, with wavelengths that are only a few feet long. The Microwave Landing System operates at 1 and 5 gigahertz, with unusually short wavelengths, each spanning only a fraction of an inch.

Inertial Navigation

Inertial navigation is not a radionavigation system, but it is discussed in the following paragraphs because it is so competitive with the GPS and other radionavigation systems and because it is so popular with so many different kinds of users, especially in the military. Two popular types of inertial navigation systems are in common use: mechanically gimballing (stable platform) systems and strapdown inertial navigation systems.

In a mechanically gimballing system, three mutually orthogonal integrating accelerometers are mounted on a swiveling platform that maintains a constant orientation in inertial space.[3] In a strapdown system the integrating accelerometers are mounted parallel to the body axis of the parent craft. Both types of inertial navigation systems employ gyroscopes to sense altitude changes and integrating accelerometers to measure the three mutually orthogonal acceleration components. The system numerically integrates the acceleration components in real time to establish the three independent velocity components. A second integration provides the three current position coordinates of the moving craft.

An inertial navigation system is a small, self-contained device with a variety of civil and military applications. However, inertial navigation is a dead reckoning technique, so it suffers from one serious limitation: drift-rate errors constantly accumulate with the passage of time. A moderately accurate inertial navigation system will build up a position uncertainty at a rate of about one mile per hour. An extremely accurate system might require ten hours to build up a similar error.

Because its drift errors relentlessly accumulate, an inertial navigation system that operates for an appreciable length of time must be updated periodically with fresh positioning information. This can be accomplished by using an external navigation reference, such as an onboard star tracker or a radionavigation system, such as Loran C or the GPS.

[3]Many practical gimballing systems swivel gently to maintain a local vertical orientation. Such a system is based on the Schuler pendulum, a theoretical construct conceptually equivalent to a simple pendulum consisting of a compact mass suspended by a 4,000-mile string. Regardless of how a Schuler pendulum is accelerated, it always maintains a continuous local vertical orientation.

JTIDS Relnav and PLRS

JTIDS Relnav and PLRS are "portable" military communication/navigation systems designed for use in local battlefield areas. The JTIDS (Joint Tactical Information Distribution System) is a ground-based time-division-access communication system coupled with a radionavigation system being financed by the U.S. Air Force. The navigation portion of JTIDS, which automatically reports the user's position, employs active and passive spherical ranging techniques to establish both the position coordinates and the velocity components of the user. This is accomplished by carefully prepositioning several "portable" radio antennas and transmitters in the local battlefield area. The navigation accuracy of JTIDS Relnav is approximately 200 to 300 feet.

JTIDS Relnav is a high-frequency line-of-sight radionavigation system. To extend its primary coverage area, its designers have rigged it so that some of the users who are within the line of sight of the ground-based transmitters can rebroadcast their pulse sequences. This allows users who are situated below the horizon with respect to the ground-based transmitters to achieve fairly accurate position-fixing solutions. JTIDS Relnav uses transmission frequencies in the 960 to 1,215 megahertz range. Its carrier waves are 10 to 12 inches long.

A conceptually similar system, the PLRS (Position Location and Reporting System), is being financed by the U.S. Army. Like the JTIDS, PLRS is primarily a time-division-multiple-access communication system, but it also uses two-way active and passive spherical ranging to provide longitude, latitude, and altitude measurements for large numbers of properly equipped military users. Typical 2σ errors are 200 to 300 feet with respect to the presurveyed transmitters located in the local battlefield area. Transmission frequencies for the PLRS are approximately 420 to 450 megahertz. This corresponds to a sinusoidal carrier wave approximately 3 feet long.

Signpost Navigation Techniques

Signpost navigation employs simple radio transmitters in large numbers to provide reasonably accurate navigation coverage for a local region, such as a construction site or a small city. The automatic vehicle location system operated by the police department in Huntington Beach, California, provides an instructive example of how a signpost navigation system can be implemented. More than 700 navigation transmitters are permanently attached to the wooden and metal telephone poles within the city limits of Huntington Beach. Each telephone pole–mounted transmitter (see Figure 3.2) broadcasts its own unique 11-bit binary code consisting of a prearranged sequence of binary 1s and 0s. That particular pulse sequence identifies the telephone pole from which the transmissions originated.

The 11-bit binary pulse train is picked up by a transceiver located in the trunk of any nearby black-and-white patrol car cruising the streets of Huntington Beach. The transceiver adds a 7-bit binary code of its own to reveal the identity of the patrol car. It then transmits all 18 bits to police headquarters on Main Street in Huntington Beach, where computers automatically track the movements of the city's fleet of black-and-white patrol cars. When the dispatcher receives a phone call reporting robbery or rape, the address is punched into the computer, which then automatically displays the identities of the three nearest black-and-white patrol cars. The dispatcher then instructs one or more of them to respond to the call.

The positioning accuracy of the Signpost Navigation System at Huntington Beach is determined primarily by the spacing between the city's telephone poles. Typically, the poles are 500 to 2,000 feet apart in the 10-square-mile city, except in the Wildlife Preserve where poles are largely absent, but where serious crimes seldom occur.

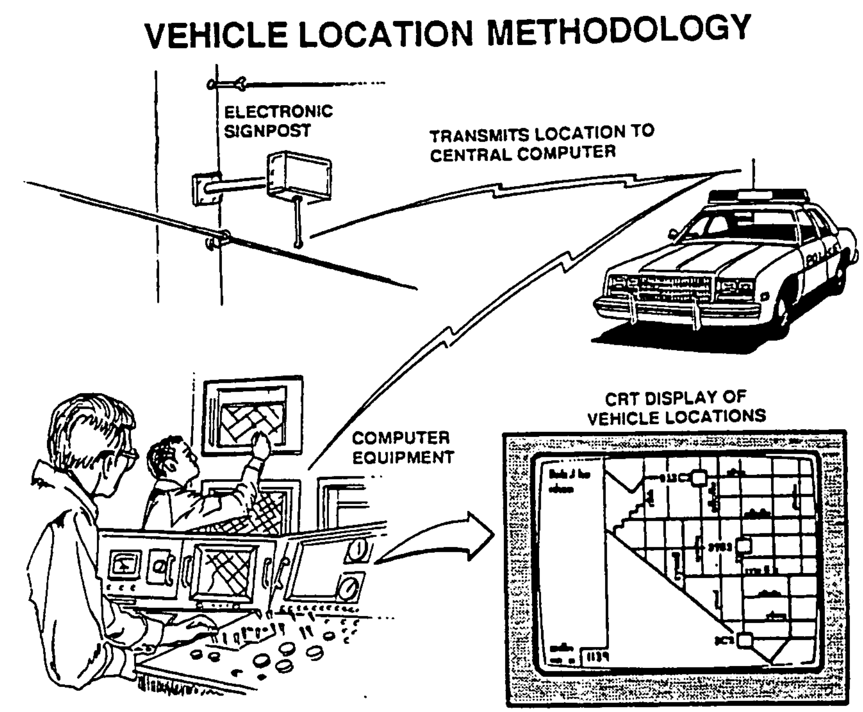


Figure 3.2 Positioning measurements for the black-and-white patrol cars in the Southern California city of Huntington Beach are determined by a signpost navigation system with 700 telephone pole-mounted transmitters. Signals from the transmitters are picked up and rebroadcast by a transceiver located in the trunk of each black-and-white patrol car. The signpost navigation system increases the efficiency of patrol car dispatching and helps insure that police officers arrive at the scene of a reported crime in minimum time.

A Sampling of Today's Space-based Navigation Systems

Space-based radionavigation systems are extremely expensive to build and install, but, because they are positioned at high altitudes in outer space, they usually provide a much broader coverage area with fewer transmitters than would be required by a ground-based system with comparable capabilities.

Transit

Transit was the world's first successful spaceborne radionavigation system. The Transit satellites were designed and built by engineers at the Applied Physics Laboratory of Johns Hopkins University and at RCA. They were launched into low-altitude polar "bird cage" orbits by the U.S. Navy aboard Thor-Delta boosters. The Transit Navigation System (SatNav) uses Doppler shift techniques to fix the positions of users all around the globe. Its basic operating principles are describe in detail in Chapter 1.

As a Transit satellite travels from horizon to horizon, the user set on the ground picks up its signals and measures the Doppler shift history, which can be represented by a gentle S-shaped curve. The exact contours of the S-shaped curve provide an unambiguous measure of the distance between the satellite's ground track and the user's location on the globe. Users who are closer to the ground trace observe an S-shaped curve that more closely resembles a step function. Those who are farther away from the ground trace observe S-shaped curves with a more gradual curvature.

Five or six Transit satellites are typically providing radionavigation coverage for SatNav users. With a constellation that large, a Transit satellite typically breaches the horizon once every hour or so. It takes the satellite 10 to 15 minutes to travel from horizon to horizon, during which a single position fix is achieved.

The accuracy of the Transit system is approximately 1,500 feet in the horizontal plane at the 2σ level (95-percent probable). Tens of thousands of Transit receivers are in use throughout the world primarily aboard large and small oceangoing vessels and smaller private boats. The dual-frequency navigation signals are broadcast at 150 and 400 megahertz. This corresponds to carrier waves a few feet long.

The Transit system provides global but intermittent navigation coverage to a large and varied group of ground-based consumers who use it with enthusiasm, despite the fact that it suffers from a number of important limitations. In particular, the Transit system provides navigation solutions in only two dimensions, it gives poor accuracy near the poles, and its performance is seriously degraded by any unpredictable motions and any altitude uncertainties during the navigation interval. And, yet, despite these inherent limitations, Transit user sets are extremely popular among navigators throughout the technological world. Tens of thousands of SatNav receivers are currently in use, 98 percent of which are owned and operated by nonmilitary personnel. For several years following the release of the signal specifications to civilian users in 1973, Transit receiver purchases consistently grew at a compound rate of 50 percent per year.

The Navstar Global Positioning System

The Navstar Global Positioning System employs passive spherical ranging techniques to determine the three-dimensional position coordinates for thousands of military and nonmilitary users on or near the earth. A Navstar receiver picks up the binary pulse trains from four or more satellites to measure the pseudo-range to each one. The resulting pseudo-ranges are then substituted into four equations in four unknowns, to solve for the three position coordinates U_x, U_y, and U_z, together with the receiver's clock bias error, c_B.

The Navstar Global Positioning System provides continuous global coverage with a two-dimensional error for the military users of 50 feet at the 50-percent probability level and 80 to 100 feet at the 2σ level (95-percent probable).

Civil users achieve a degraded 2σ error of 330 feet in the horizontal plane.

Saving Race Car Drivers From Outer Space

Serge Goriely was lucky that a specially equipped weather satellite was providing emergency navigation services when his four-wheel drive Citroen whipped out of control in a remote African desert. Otherwise, he would probably not be alive today. Goriely, a 21-year-old professional race car driver, suffered a fractured skull and lay motionless beside his crushed vehicle after it crashed, rolled over several times, and threw him out on the burning sand.

Fortunately, Goriely's car was equipped with a SARSAT search-and-rescue beacon that was automatically activated when he careened off the road. Within seconds, the unit began sending a distress signal through outer space for relay back to Paris. Seventeen minutes later, a doctor was dispatched to the scene of the accident by helicopter, arriving there 79 minutes after the crash. He managed to patch Goriely back together and then admitted him to a nearby hospital for several days recuperation before his colleagues knew for sure that he was to join the 344 other lucky individuals whose lives had been saved by the SARSAT peering down from outer space.

Teams of technicians in the United States, Canada, France, Russia, and seven other technological nations work together to help make sure that SARSAT stays on the air. Emergency beacons—space-age cries for help—stream up to various Russian and American satellites from planes, boats, and even battered race cars for immediate retransmission to rescuers on the ground. The SARSAT units are designed to broadcast coded messages that tell who is in trouble and their approximate location.

Before the SARSAT became available, average notification time for a missing aircraft was 36 to 48 hours. However, if lives are to be saved, rescue efforts must usually be completed within 24 hours or less. With four active SARSATS in a small orbiting constellation, an emergency signal from Africa or any other remote location can be picked up by ground monitoring systems always within one hour after the emergency occurs.

When it is fully operational, the Navstar constellation will consist of 21 satellites plus 3 active on-orbit spares positioned in six orbit planes. Carrier wave frequencies for all the GPS satellites are centered at 1,575.42 and 1,227.6 megahertz for the L_1 and L_2 navigation frequencies, respectively.

The French Argos

The French Argos (see Figure 3.3) is a highly popular and relatively inexpensive space-based radionavigation system. American weather satellites, such as the Tiros relay navigation signals from the Argos transmitters mounted on slowly moving platforms, such as drifting buoys and weather balloons. The Argos system employs bent-pipe radionavigation techniques, whereby the navigation signals follow a sharp angular route from the buoy up to an orbiting satellite and then back down to a special computer processing facility located on the ground. The navigation solution is handled by a dedicated computer processing facility on a non-real-time basis.

Three-dimensional solutions, such as those needed for floating balloons, are typically in error by approximately 10,000 feet. Simpler two-dimensional solutions, such as the ones used in connection with drifting buoys, typically provide 3,000-foot navigation errors. The French Argos is used for a variety of practical applications, including earthquake fault monitoring and the determination of the migration routes of relatively large animals, such as deer and moose.

Side-by-side Performance Comparisons

The transmission frequencies for a sampling of today's most popular radionavigation systems are compared in Figure 3.4. The systems listed on the right-hand side of the figure rely on high-frequency transmissions, so they tend to yield more accurate navigation solutions. These include the Navstar GPS, the Microwave Landing System, the JTIDS relnav, and the Army's PLRS.

The Navigation systems spotted on the left-hand side of the figure, such as Omega and the Loran, rely on lower frequency transmissions, which generally result in relatively inaccurate navigation. The transmission frequencies for Omega and Loran were specifically selected so that their carrier waves would reflect off the charged particles in the earth's ionosphere. This greatly increases the coverage regimes, but at a substantial sacrifice in navigational accuracy.

Comparisons between the anticipated positioning errors and the operating ranges for various popular radionavigation systems are presented in Figure 3.5. The navigation errors all apply to the 2σ level (95-percent probable). Notice that the horizontal scale ends at 11,000 nautical miles (the half-circumference of the earth). When a system's operating range is posi-

THE FRENCH ARGOS SYSTEM

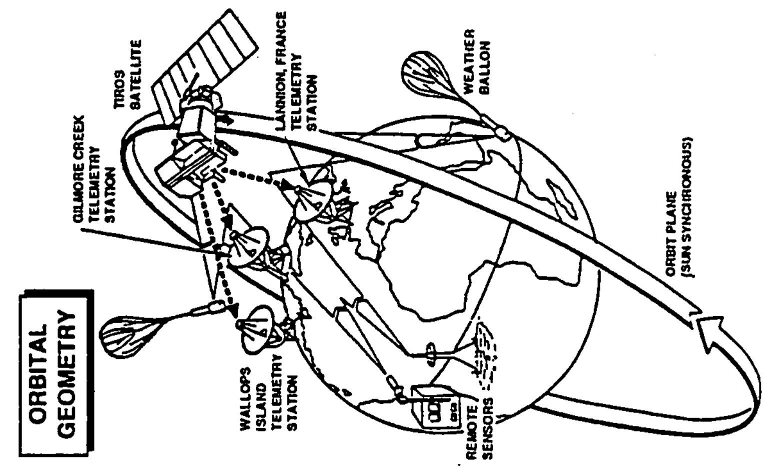


Figure 3.3 The French Argos is a bent-pipe radionavigation system used to track drifting buoys and migrating animals to an accuracy of a few thousand feet. A continuous tone (sinusoidal carrier wave) is relayed from each transmitter up to an orbiting satellite. Then it is sent back down to a ground-based computer processing facility, where the navigation solution is executed.

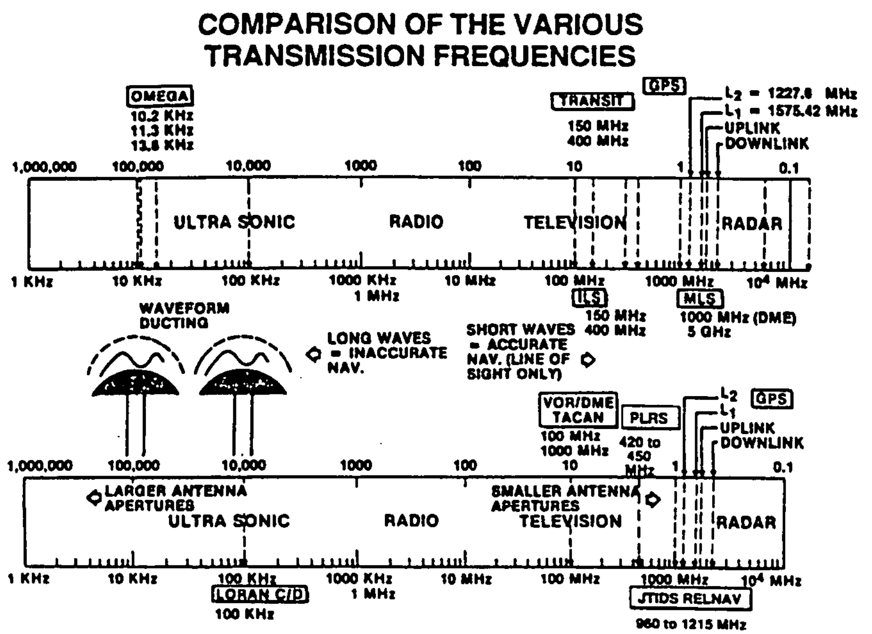


Figure 3.4 Radionavigation systems, such as Loran and Omega achieve broad-area coverage by using very-low-frequency transmissions that reflect off the ionosphere. Unfortunately, the resulting navigation solutions are not very accurate. High-frequency systems, such as MLS and JTIDS Relnav, achieve enhanced accuracies but with limited line-of-sight coverage. The GPS, the Soviet Glonass, and other proposed space-based radionavigation systems combine good accuracy with global coverage. This is accomplished by relying on high-frequency carrier waves transmitted from high-altitude platforms in space.

tioned on the 11,000-nautical-mile line at the far right, it provides essentially global coverage.

Radionavigation systems capable of providing global coverage include the Navstar GPS, the Transit Navigation System, and Omega. At the 2σ probability level, the Navstar GPS yields a positioning error of 80 to 100 feet when it is operated in its undegraded military mode. Unauthorized (civil) users, who are purposely restricted from achieving the full military accuracy of the system, typically experience a pseudo-ranging navigation error of 330 feet. The 2σ error for the Transit Navigation System is about 20 times bigger than the comparable error for the Navstar GPS. The Omega also provides essentially global coverage, but with a much larger positioning error of 2 to 4 nautical miles. Thus, the Omega System is about 100 times less accurate than the Navstar GPS. Some short-range positioning systems, such as ILS and MLS, achieve positioning accuracies that are fully competitive with the Navstar, but only within a small line-of-sight coverage area.

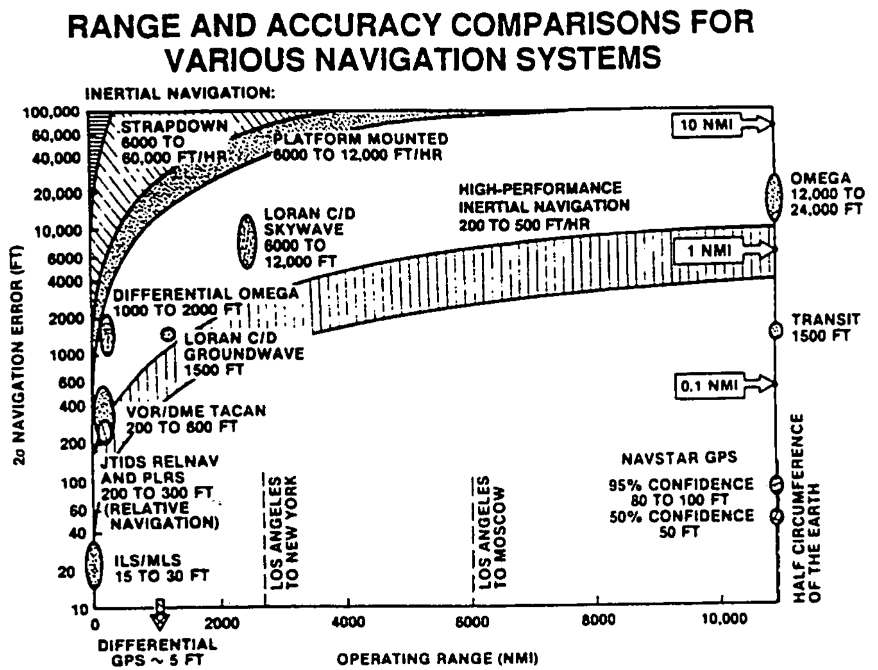


Figure 3.5 Worldwide navigation coverage is provided by the Navstar Global Positioning System, which yields a military accuracy of 80 to 100 feet 95 percent of the time. Other radionavigation systems with global coverage characteristics include the space-based Transit, which is about 20 times less accurate than the GPS, and the ground-based Omega, which is 100 times less accurate. Short-range systems with roughly comparable performance—within their limited coverage regimes—include the Microwave Landing System, which is used in landing specially equipped airplanes, and the JTIDS Relnav, a military system designed for use in local battlefield areas.

The Navstar Global Positioning System provides today's navigators with a number of advantageous characteristics. These include passive ranging with an unlimited number of users, accurate position and velocity measurements, good jamming immunity, precise time synchronization, and high-dynamic operation. The Navstar GPS also provides continuous navigation coverage 24 hours a day, with a fresh navigation solution every second or so. The receivers used in connection with some alternate navigation systems may be a bit cheaper, but no other system can provide comparable services at a comparable price.

4

User-Set Architecture

The electromagnetic signals picked up by a Navstar receiver are surprisingly whispy and tenuous. Their energy density is roughly equivalent to the illumination from the brake light of a Lincoln Town car seen by another driver 1,500 miles away. Stand on the observation deck of the Chicago Sears Tower, looking toward the western sky, and your face will be bathed by a comparable amount of energy from a 15-watt Christmas tree bulb clipped to the Nativity scene in San Francisco on the Pacific Coast.

And yet, despite their ephemeral nature, those faint Navstar signals can be received by surprisingly small antennas, some of which are only two inches across. Once they have been picked up, the Navstar navigation signals can be processed by miniature receivers, some as small, compact, and inconspicuous as a king-size pack of cigarettes.

Many modern receivers are jam-packed with today's most advanced gallium-arsenide computer chips, chips that feature low power consumption, fast processing, and glitch-free operation. Working with highly efficient antennas, advanced architectures, digital processing techniques, and clever software routines, today's electronic engineers are turning the next generation of Navstar receivers into amazingly capable machines.

The Major Components of a Typical Navstar Receiver

Practical and accurate navigation services were successfully provided by the earliest Navstar receivers, but, generally speaking, those early devices were bulky, heavy, expensive, and difficult to operate. Even a reasonably compact model, such as the Texas Instruments 4100, weighed 40 pounds and was roughly the size of a small electric typewriter. The initial version retailed for

$139,000. Later it was reduced to $119,000, before it was replaced by a more competitive design.

A few of today's models are only a bit bigger than pocket calculators some sell for only a few hundred dollars each. But, regardless of size, price, or complexity, a modern receiver can usually be broken down into five major subassemblies:

1. The receiver antenna and its associated electronics
2. The tracking loops
3. Navigation processor
4. Power supply
5. Control display unit

Figure 4.1 highlights various interactions between these major components, and summarizes the critical functions performed by each one of them.

The Receiver Antenna and Its Associated Electronics

A Navstar antenna is designed to pick up the right-hand circular-polarized L_1 and/or L_2 carrier waves from selected satellites located above the horizon. It then concentrates and amplifies the modulated carrier waves, and converts their electromagnetic energy into an equivalent electric current still containing the appropriate C/A-code, P-code, and data stream modulations. Often, the Navstar antenna is physically isolated from multipath reflections by means of a flat metal mount called the "ground plane," which helps prevent smearing and distortion of the binary pulse trains.

The L-band signals picked up by the antenna are routed through a preamplifier circuit that boosts their power level for easier processing by the downstream electronic devices. The signals from the antenna are often routed to the receiver through a coaxial cable which also carries electrical power from the receiver to the antenna's preamplifier circuits.

The Tracking Loops

Two different types of tracking loops are executed by a Navstar receiver: (1) the *code-tracking loop*, which tracks the C/A- and/or P-code pulse trains to obtain the signal travel time for each relevant satellite, and (2) the *phase lock loop*, which tracks the satellite's carrier wave to obtain its instantaneous Doppler shift. Code tracking allows the receiver to measure the appropriate *pseudo-ranges* to the four (or more) satellites necessary for an accurate positioning solution. Doppler shift tracking allows the receiver to measure the corresponding *pseudo-range rates* so it can estimate accurate values for the receiver's three mutually orthogonal velocity components.

A special mixer (multiplier circuit) steps down the frequency of the carrier

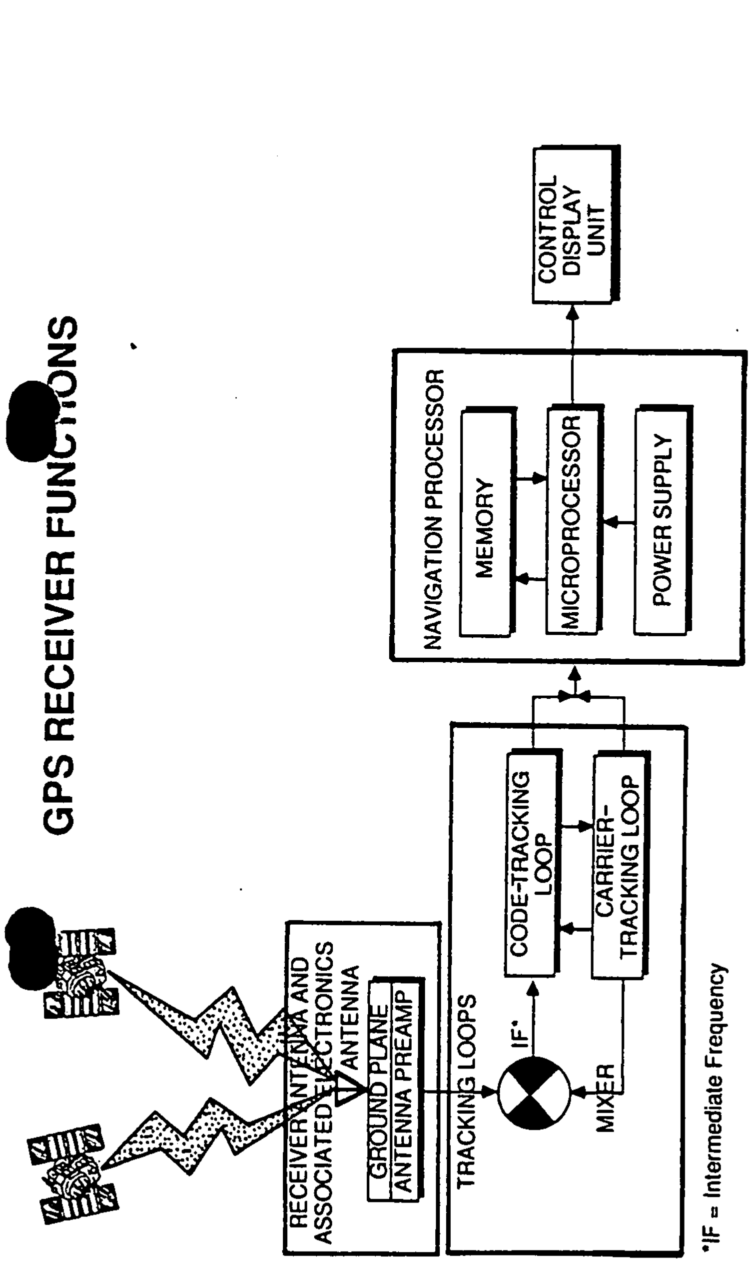


Figure 4.1 This simple block diagram highlights the major component subassemblies of a typical Navstar receiver. The receiver antenna picks up the signals from the satellites, and amplifies them before they are fed into the two tracking loops that lock onto the carrier waves and the appropriate binary codes to obtain pseudo-range and the Doppler shift measurements. Once these measurements have been made, the microprocessor automatically determines the user's current position coordinates and velocity components, which are displayed by the control display unit in a convenient human-oriented format.

waves from gigahertz to megahertz before they enter the tracking loops. Carrier waves at an intermediate frequency are created by mixing the incoming satellite signals with a pure sinusoidal oscillation created by a voltage-controlled crystal oscillator. The intermediate carrier wave still contains all of the C/A-code, P-code, and data stream modulations broadcast by the satellite, but they are all shifted to the intermediate beat frequency, which is much easier for the downstream circuits to process.

The code-tracking loop automatically generates and time shifts a replica of the 1-million bit-per-second C/A-code coming down from each satellite to bring the replica into precise correspondence with the satellite's C/A-code. When matchup (auto-correlation) has been achieved, the auto-correlation function suddenly jumps from a value of 0 to a value of 1.

Auto-correlation (lock-on) allows the code-tracking loop to measure the instantaneous pseudo-range to the satellite and also to decode its 50 bit-per-second data stream. Most P-code receivers use the Handover Word located in each 6-second subframe of the data stream to substantially decrease the time required to lock on to the 10-million bit-per-second P-code.

The *carrier-tracking loop* uses a voltage-controlled crystal oscillator to create a replica of the incoming carrier wave. It then beats the two carrier waves together to determine their beat frequency, an indirect measure of their relative Doppler shift. Carrier-wave tracking is often accomplished by using some variation of the Costas Loop, which was developed and perfected in 1959 by J. P. Costas at General Electric in Schenectady, New York.

Navigation Processor

The navigation processor uses the pseudo-range and the Doppler shift measurements to determine the instantaneous position coordinates and the velocity components of the Navstar receiver. The solid-state processing circuits also handle the satellite selection algorithms, any necessary coordinate transformations, the Kalman filtering techniques, and the routing calculations needed for efficient waypoint navigation.

The memory units in the navigation processor provide erasable "scratch pad" storage for the various types of computations. Each time the receiver is turned off, nonvolatile portions of its microprocessor memory are used to save the last set of position coordinates, together with the last set of almanac constants. When the receiver is turned back on again, these values are used to obtain the "first guess" estimates of position and to determine which four satellites are the most favorably positioned for accurate navigation.

For some specialized applications the microprocessor's memory is used to store large arrays of pseudo-range measurements for precise postprocessing. In postprocessing applications, improved values for the satellite's ephemeris constants obtained after the fact are used to enhance the accuracy

of delayed navigation solutions. Surveying and military test range applications, for instance, obtain substantial accuracy improvements by using appropriate post-processing techniques.

Power Supply

The DC power needed to operate a Navstar receiver is usually provided by disposable lead-acid batteries or rechargeable nickle-cadmium (Ni Cd) batteries. But the electrical systems of trucks and tanks can also provide the requisite power. In some cases, the power supply module includes power conversion devices (AC to DC) and the devices needed to condition and convert the recharging power supply.

Control-Display Unit

The control display unit is a convenient man-machine interface between the user and a Navstar receiver. It is designed to accept inputs and instructions from the user, including the desired operating modes, stationary and moving waypoints, coordinate systems, and any necessary encryption keys.

The current position and velocity are automatically displayed on light-emitting diodes (LEDs) or cathode ray tube (video) screens. The control display unit also displays the exact time and waypoint navigation instructions under efficient user control.

Choosing the Proper User-set Architecture

As Figure 4.2 indicates, three different types of Navstar receivers with fundamentally different architectures are currently available in the commercial marketplace:

1. Continuous-tracking receivers
2. Slow-sequencing receivers
3. Fast-sequencing receivers

A *continuous-tracking receiver,* which is also called a *multichannel* receiver, tracks four or more Navstar satellites continuously with a separate front-end being devoted to each satellite being tracked. It gains uninterrupted access to the 50-bit-per-second data stream superimposed on the transmissions being received from each satellite. Continuous-tracking receivers are more expensive than the two alternate architectures, but they are simpler in concept and can operate successfully under high-dynamic, military conditions.

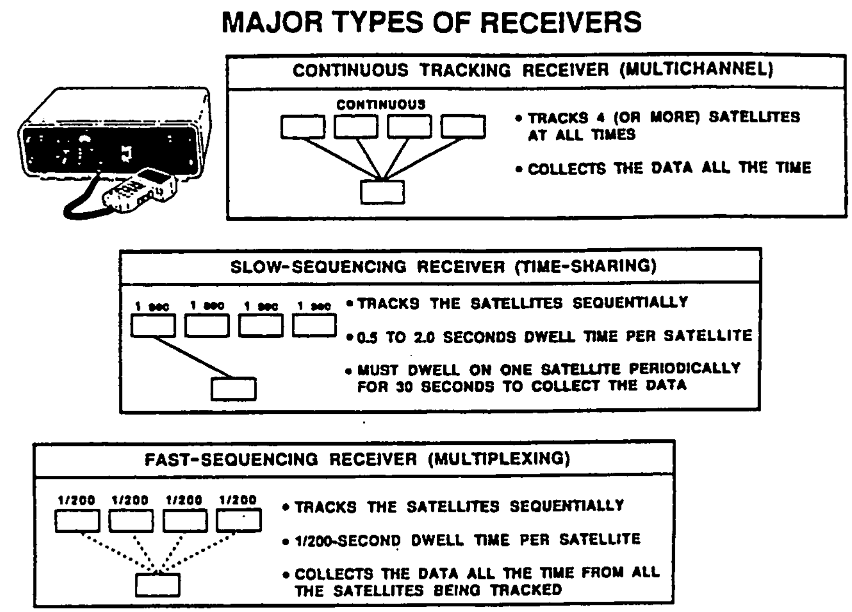


Figure 4.2 Three major types of pseudo-ranging receivers are currently available in the commercial marketplace. Though costly, the *continuous-tracking receiver* is an excellent choice for applications that require a rapid time-to-first-fix, high-dynamic operation, and/or good jamming immunity. The *slow-sequencing receiver* is a cheaper alternative for less demanding applications. The *fast-sequencing receiver* is generally between the two in terms of performance and price.

A *slow-sequencing receiver,* which is also called a *time-sharing receiver,* tracks four or more Navstar satellites sequentially. It typically dwells on each satellite for one or two seconds before moving on to the next satellite in sequence. A slow-sequencing receiver is similar in concept to a time-sharing computer network in that the demands on the system are serviced sequentially using the same hardware. A slow-sequencing receiver typically dwells on each satellite for two seconds or less, so it must interrupt its processing sequence periodically in order to obtain at least one 30-second frame from the satellite's 50-bit-per-second data stream.

A *fast-sequencing receiver,* which is also called a *multiplexing receiver,* tracks four or more Navstar satellites sequentially, but it dwells on each of them for an extremely brief interval. If, for instance, a multiplexing receiver is sequencing between four different satellites, it might dwell on each one for one two-hundredth of a second. Thus, it gets back to each satellite just in time to pick up the next bit in its 50-bit-per-second data stream. In this way a fast-sequencing receiver can gain access to all of the 50-bit-per-second data streams from all four of the satellites at all times.

Performance Comparisons

Of course there are various performance tradeoffs between the three fundamentally different types of pseudo-ranging receivers. In particular, they differ with respect to these three measures of performance:

1. Time-to-first-fix
2. Dynamic operating range
3. Jammer-to-signal ratio

The *time-to-first-fix* is the amount of time required for a Navstar receiver to obtain its first successful position fix. As Table 4.1 indicates, a typical continuous-tracking receiver might require 1.3 minutes to obtain its first position fix, compared with 4.0 minutes for a comparable slow-sequencing receiver. The fast-sequencing architecture is between the two. It typically requires 2.5 minutes to obtain its first position fix. Owners may become impatient, but most civilian users can tolerate any of these three time-to-first-fix intervals. For some military applications, however, such as submarine navigation, a short time-to-first-fix can be vital to survival.

The *dynamic operating range* for a Navstar receiver provides a convenient numerical measure for the acceleration and velocity uncertainties under which it can operate successfully. A well-designed continuous-tracking receiver, for instance, might operate successfully in a 10-g dynamic environment, compared with a 1-g environment for a comparable slow-sequencing receiver. A fast-sequencing receiver of similar design might function well in an intermediate dynamic environment of about 4 g's. Thus, a continuous-tracking receiver is suitable for use aboard high-performance military jets, which, except for emergencies, stay well below 9 g's. A comparable slow-sequencing receiver is suitable for use aboard a ground-based vehicle, such as a tank or an army truck. A fast-sequencing receiver is suitable for use aboard vehicles that experience intermediate dynamics, such as jet-powered boats and crop dusting planes.

The *jammer-to-signal ratio* for a Navstar receiver quantifies the amount

Table 4.1 The performance capabilities of various types of receivers[1]

Type of receiver	*Typical time To first fix (min)*	*Typical dynamic operating range (Gs)*	*Typical jammer-to-signal ratio (dB)[2]*
Continuous tracking	1.3	10	−10
Slow sequencing	4.0	1	−11
Fast sequencing	2.5	4	−16

[1]A variety of engineering assumptions enter into estimates of this type. The values presented in this table are intended to indicate trends, not to characterize the salient performance characteristics associated with receivers of each type currently available for purchase.
[2]Relative values.

of jamming immunity it provides. If a continuous-tracking receiver is baseline at −10 dB, then comparable slow-sequencing and fast-sequencing receivers might typically provide −11 dB and −16 dB jammer-to-signal ratios, respectively. Thus, a slow-sequencing receiver is only slightly more susceptible to jamming than a multi-channel receiver, but is considerably more ~~less~~ immune to jamming than a fast-sequencing (multiplexing) receiver. Fast-sequencing architectures are thus unsuitable for use aboard military vehicles that must operate in unfriendly environments populated by enemy jamming devices.

Selecting the Antennas

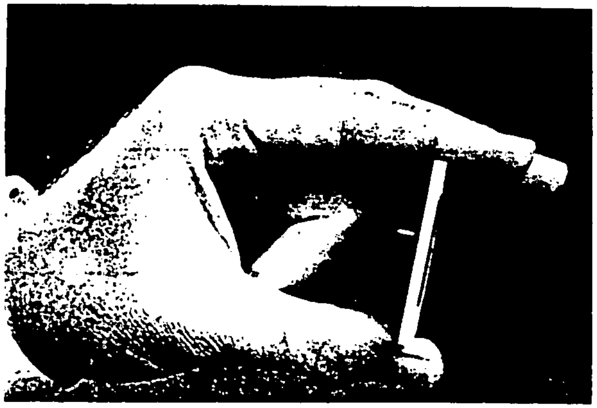
The L-band transmissions streaming down toward earth from the Navstar satellites arrive with extremely low power densities, so reasonably efficient user-set antennas are needed to pick up the faintly modulated signals they contain. The satellite transmissions are all right-hand circular polarized, so the user-set antennas must also be right-hand circular polarized. However, the antennas need not be bore-sighted toward any particular sector of the sky to acquire the signals from the Navstar satellites. For efficient operation, the user-set antennas must be positioned so that they are free of major obstructions. Thick foliage, for instance, blocks the satellite signals, especially if the foliage is dense enough to stop the light from the sun.

A few years ago a team of researchers at the FAA research center near Atlantic City, New Jersey, conducted a series of tests to determine if the Navstar signals could successfully penetrate a helicopter rotor blade. They found that rotor-blade blockage was not a major problem—unless the antenna was positioned under the hub of the rotor blade where it was blocked by essentially solid metal. Intermittent interruption by the whirling rotor blades did not interfere with accurate Navstar navigation.

Operational Navstar receivers employ antennas in a variety of shapes, including dome antennas, patch antennas, volute (spiral) antennas, and blade antennas. Recently, Ball Aerospace has successfully marketed a square ceramics microstrip antenna only 2 inches on a side (see Figure 4.3). The C/A-code version (L_1 carrier wave only) is 0.1 inches thick and weighs only one ounce. Another version, which is rigged to pick up both the L_1 and the L_2 signals, has the same 2-inch cross section, but it is 0.3 inches thick. It weighs 2.7 ounces. Power-limited and size-limited designs—such as hand-held receivers and those designed for use in connection with automotive and avionics-type applications—are using large numbers of these tiny micro-strip antennas.

A few high-performance military applications call for electronic null-steering antennas. A null-steering antenna is an electronically steered phased array usually constructed from seven antenna elements mounted side by side on a flat ground plane. The entire unit is flush-mounted with the skin of an aircraft. With null-steering techniques the nodes of the antenna

CERAMIC GLOBAL POSITIONING SYSTEM ANTENNAS



BALL AEROSPACE GPS ANTENNA

- PATENTED CERAMICS MICRO-STRIP ANTENNA
- 2" x 2" AND ONLY 0.1" THICK: ONE OUNCE
- THICKER ANTENNA (0.3" THICK WEIGHING 2.7 OUNCES) RECEIVES BOTH L_1 AND L_2 BROADCASTS

Figure 4.3 Ball Aerospace produces two small micro-strip antennas for use in connection with Navstar receivers. Both are 2-inch squares. The single-frequency L_1 version is one-tenth of an inch thick and weighs 1 ounce. The more complicated L_1/L_2 version is three-tenths of an inch thick. It weighs 2.7 ounces. According to Ball Aerospace brochures, these 2-inch antennas match the performance capabilities of the 5-inch antennas that the company produced in 1975.

pattern are automatically directed toward the satellite signals. This increases the average jamming immunity of the unit by a substantial amount, thus opening up highly demanding military applications and making other military applications considerably more successful.

Selecting the Proper Computer Processing Techniques

The Navstar Global Positioning System represents a beautiful marriage between space technology and computer technology. The five-channel military receiver built by Rockwell Collins, for instance, is computationally equivalent to a desk-top computer. It contains five front-end chips, each of which can perform 200,000 floating-point operations per second. A sixth chip capable of performing 400,000 operations per second handles the navigation solution. Thus, a typical military receiver of modern design is capable of performing at least 1,400,000 mathematical operations every second.

The software routines in a modern receiver are also surprisingly extensive. Sixty thousand lines of code are needed for successful operation of a five-channel military receiver. At Rockwell International's Government Avionics Division in Cedar Rapids, Iowa, software development required the services of 65 full-time professional programmers. Modularization, layered architecture, and effective data-hiding techniques were coupled with structured programming and professional software engineering, but developing the necessary software was still a difficult undertaking.

Solving for the User's Position

How does a Navstar receiver obtain a pseudo-range measurement to each of the relevant Navstar satellites? Each satellite repeatedly broadcasts its own unique C/A-code, a prearranged sequence of binary 1s and 0s that identifies it to the receiver, which attempts to lock onto the satellite by generating an identical sequence of binary 1s and 0s. Of course, the two pseudorandom codes will be offset (displaced) with respect to one another. In order to "lock on" to the signal coming down from the satellite, the user set automatically slews (shifts) its sequence of binary 1s and 0s to bring the two sequences into correspondence. When this occurs, the auto-correlation function suddenly jumps from a value of 0 to a value of 1, as shown in Figure 4.4. Once it has locked onto four or more GPS satellites, a C/A-code receiver is ready to perform its first navigation solution.

P-code receivers go through a more elaborate two-step procedure. First the receiver locks onto the C/A-code pulse sequence in the manner just described. This allows it to gain access to a special "Handover Word" in each subframe of the 50-bit-per-second data stream. The Handover Word contains a set of constants that allow the receiver to generate the current P-code, thus greatly shortening the necessary search.

P-code receivers have a number of intrinsic advantages over their simpler C/A-code counterparts. In particular, a P-code receiver provides more accurate navigation, enhanced jamming immunity, and better multipath rejection.[1]

Once a Navstar receiver has successfully locked on to four or more Navstar satellites, it can insert the four measured pseudo-ranges into a system of four equations in four unknowns so that it can solve for its position coordinates U_x, U_y, and U_z and its clock bias error, C_B. By measuring the Doppler shift (compression of the sinusoidal carrier waves) from the same four Navstar satellites, the receiver can also determine its three mutually orthogonal velocity components. Undegraded velocity errors as small as 0.3 feet-per-second (1σ) are relatively easy to achieve.

[1]Multipath interference occurs when the signals from a Navstar satellite reflect off adjacent objects, such as a nearby lake or the wings of a plane. Multipath interference smears the binary pulses, thus reducing the accuracy of the pseudo-range measurements. Annoying "ghosts" on a T.V. screen are created in a similar manner.

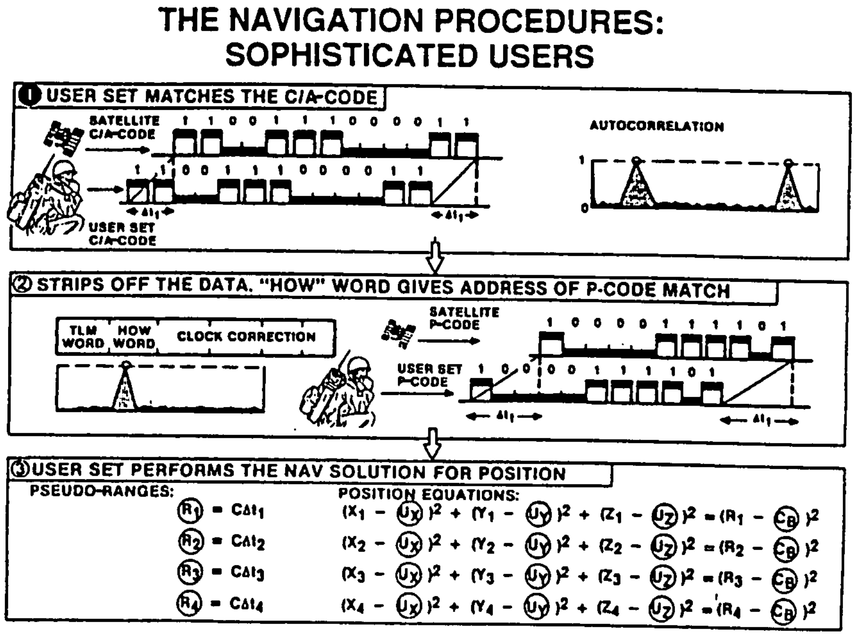


Figure 4.4 Most P-code receivers go through this relatively complicated two-step procedure to lock onto the P-code pulses of each favorably situated satellite. First the receiver generates the appropriate 1-million bit-per-second C/A-code, and then slews (shifts) that code to bring it into correspondence with the identical C/A-code coming down from the satellite. It then decodes the 50-bit-per-second data stream, which contains the Handover Word in each 6-second subframe. The Handover Word helps the receiver generate the satellite's current P-code and match it after only a short search.

Computing and Interpreting the Geometrical Dilution of Precision

The accuracy of a Navstar navigation solution depends on two key factors: (1) the accuracy with which the receiver can measure the slant range to the appropriate satellites, and (2) the geometrical locations of the satellites with respect to one another, as seen from the user's point of view. Unfavorable satellite geometry occurs, for instance, whenever the satellites being tracked happen to lie along a straight line across the sky or whenever they are bunched up together.

To obtain the smallest navigation error, the satellites should be widely dispersed with big angles betwen them, as seen from the user's location. For the Navstar constellation the optimum geometrical pattern (biggest possible tetrahedron) occurs when one of the satellites is directly overhead, and the other three are spaced 120 degrees apart along the horizon. The so-called

Table 4.2 Geometrical Dilution of Precision The Various Types

Type Of GDOP	*Interpretation*	*Coordinates Involved*	*Typical interested User*
GDOP	Geometrical Dilution of Precision[1]	U_x, U_y, U_z, U_t (3-D coordinates plus time)	Mostly of theoretical interest Moving time sync users
PDOP	Position Dilution of Precision	U_x, U_y, U_z (3-D coordinates)	Air-related and space-related users
HDOP	Horizontal Dilution of Precision	U_x, U_y (local horizontal coordinates)	Maritime users
VDOP	Vertical Dilution of Precision	U_z (Altitude)	Air-related users
TDOP	Time Dilution of Precision	U_t (Time)	Time sync users

[1]GDOP (Geometrical Dilution of Precision) is a specific term that refers to navigation precision having to do with U_x, U_y, U_z and U_t. It is also a *generic* term that refers to *any* of the five different dilutions of precision listed in this table.

Geometrical Dilution of Precision (GDOP) provides a convenient numerical measure of how well the satellites are mutually positioned. The smallest (most favorable GDOP) occurs when the unit tetrahedron has the maximum possible volume. The unit tetrahedron is formed by pointing four unit vectors from the receiver toward the four satellites, and then closing off the tetrahedron that results.

As indicated by Table 4.2, five popular types of GDOPs are in common use; the non generic GDOP is mostly of theoretical interest. It relates to the geometrical error-magnifier in the three position coordinates U_x, U_y, and U_z, combined with the error in time, U_t.

The *Position Dilution of Precision* (PDOP) relates to the position uncertainty in the three mutually orthogonal position coordinates U_x, U_y, and U_z. PDOP is important to air-related users. The *Horizontal Dilution of Precision* (HDOP) relates to the two mutually orthogonal position errors in the horizontal plane. HDOP is of interest to maritime users who already have a good handle on their vertical position—since they are usually sitting on the surface of the sea.

The *Vertical Dilution of Precision* (VDOP) relates to the error in the vertical (altitude) component. This measure of performance is important to airplane pilots who are attempting to execute precise landings at non instrumented airfields. *Time Dilution of Precision* (TDOP) relates to the error in the current time. The TDOP value is important to scientists and engineers who are attempting to mutually synchronize distant atomic clocks.

Under optimal conditions, when one satellite is directly overhead and the other three are on the horizon 120 degrees apart, the PDOP equals $\sqrt{8/3}$, or 1.639. To obtain the current three-dimensional position error, we multiply the 1σ ranging error to the satellites by the PDOP.

In practice, a PDOP of 1.639 is seldom achieved, because we usually impose a mask angle below which the navigation signals from the GPS satellites will not be used. The mask angle helps minimize the distortions in the navigation signal that would otherwise occur when the carrier waves travel through the thicker portions of the atmosphere down near the horizon. Depending on the application, mask angles typically range between 5 and 15 degrees.

Ranging Error Budgets

The observed ranging errors to the Navstar satellites can be estimated by constructing a user-equivalent range error budget that lists the values of the various independent error components. A typical sample for P-code navigation is represented by the bar charts at the top of Figure 4.5. Notice that the components are the satellite clock and ephemeris errors that, taken together, amount to 12.8 feet. Other errors include the unmodeled iono-

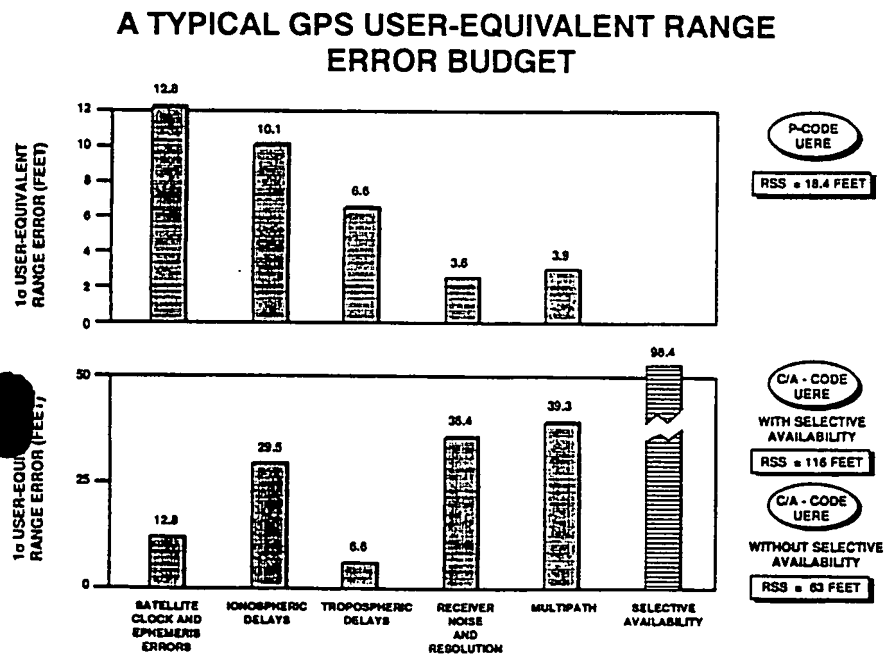


Figure 4.5 The two rows of bar charts in this figure represent error components arising from the measurement of the signal travel time between the user and a typical GPS satellite. When the various error components are combined, the P-code users end up with a total 1σ ranging error of 18.3 feet. The corresponding 1σ errors for C/A-code users with and without selective availability are 116 and 63 feet, respectively.

spheric and tropospheric delays, receiver noise and resolution, and the multipath error. An estimate of the total combined ranging error can be obtained by assuming that the various error components are statistically uncorrelated. Under this assumption the combined 1σ error is equal to the root-sum-square of the various error components. For the specific error components listed at the top of Figure 4.5, this combined error amounts to 18.4 feet (RSS).

The error components for C/A-code navigation are represented by the bar charts at the bottom of Figure 4.5. Notice that the satellite clock and ephemeris errors are identical to the ones for P-code navigation, but the error associated with the ionospheric delay is three times larger because the precise dual-frequency ionospheric correction is not available to the C/A-code users. They must, instead, employ a less accurate polynomial approximation whose coefficients are obtained in real time from the satellite's data stream. The tropospheric error is the same for P-code and C/A-code navigation (6.6 feet), but the receiver noise and resolution and the multipath errors are both 10 times larger because of the lower chipping rate associated with C/A-code navigation.

When selective availability is implemented, the extra ranging error purposely introduced will, on the average, amount to 98.4 feet, and the corresponding total root-sum-square ranging error will equal 116 feet. The C/A-code navigation error, without selective availability, will equal 63 feet.

An approximate value for the 1σ navigation error associated with the Navstar navigation system can be obtained by multiplying the combined total ranging error by the worldwide time-averaged PDOP which, depending on the precise Navstar constellation, amounts to approximately 2.3. When this PDOP value of 2.3 is multiplied by the 18.4-foot P-code ranging error, an average 50-foot navigation error results.

Kalman Filtering Techniques

The various navigation errors quoted so far correspond to a pseudo-ranging "point solution," but, with effective Kalman filtering, substantial error reductions can sometimes be achieved. Kalman filtering is a mathematical technique for combining and smoothing a sequence of navigation solutions to obtain the best real-time estimate of the current position. For stationary users the Kalman filter might involve only four state variables (types of unknowns to be combined and smoothed). The usual selection for the four state variables would be U_x, U_y, and U_z plus the clock-bias error, C_B.

For an application with moderate vehicle dynamics, an eight-state Kalman filter will usually suffice. Typically, its state variables will consist of the three position coordinates, U_x, U_y, and U_z; the three velocity components, $\dot{U}_x$, $\dot{U}_y$, and $\dot{U}_z$; the clock bias error, C_B; and the clock-bias error rate, $\dot{C}_B$. High-dynamic users typically employ an 11-state Kalman filter with

these 8 state variables plus the three acceleration components, $\ddot{U}_x$, $\ddot{U}_y$, and $\ddot{U}_z$.

For high-dynamic applications in which a GPS receiver is integrated with an inertial navigation system, the number of state variables can quickly increase to a much larger number with the addition of accelerometer bias terms, tilt angles, drift-rate terms, and so on.

Military receivers often employ Kalman filtering techniques to compute and display the *figure of merit*, a real-time estimate defining the current error in the navigation solution. A figure of merit of 3, for instance, indicates that the current navigation error lies somewhere between 164 to 246 feet (50 to 75 meters) a figure of merit of 6 indicates a navigation error of 656 to 1,650 feet (200 to 500 meters).

The Navstar receiver determines the current value for its figure of merit by comparing the real-time error statistics coming out of its Kalman filter with previously computed statistics stored in tabular form in the receiver's memory. These previously stored error statistics take into account a large number of parameters and conditions, such as the number of satellites being tracked, the aiding units currently being used, the operating state of the receiver, and so on. With Kalman filtering, the navigation solution typically converges to a substantially improved accuracy level within a few dozen seconds.

In one series of computer simulations, for instance, a military airplane's dynamic maneuvers were simulated with great fidelity as it descended to land on an aircraft carrier steaming forward at a constant speed. During the first 20 seconds of that differential navigation simulation, the relative error between the two moving vehicles converged to within 10 feet. During the next 80 seconds, the relative error shrank to about 3 feet.

Comparable results have been demonstrated under actual flight conditions in which airplanes are flown around racecourse trajectories. In this case the actual location of the plane is determined by mounting corner-cube reflectors on its wings and fuselage to retroreflect ground-base laser beams. Procedures of this type can be used to measure and compare the accuracy of various Kalman filters and the other contributors to the navigation error.

5

User-set Performance

The average positioning error for Navstar navigation is often quoted as a single number, such as 50 feet. But, actually, as Figure 5.1 indicates, at least six grossly different error levels can be specified, depending primarily on which operating mode the receiver uses to obtain its navigation solution. The six modes of operation, which are listed in Figure 5.1, can be partitioned into these two broad categories:

1. Absolute navigation
2. Differential navigation

In the *absolute navigation* mode the receiver determines its position absolutely with respect to a specific set of map coordinates, such as longitude and latitude, as defined in the WGS-84 map coordinate system. In the *differential navigation* mode the receiver determines its position with respect to a fixed base station. The base station picks up the L-band signals from the Navstar satellites in real time and transmits information on its current navigation solution to other, nearby receivers. Within a small local area, differential navigation is considerably more accurate than absolute navigation because many of the errors are common to the two solutions and hence they tend to cancel out.

Accuracy Estimates for Various Methods of Navigation

As the three horizontal stripes in the upper right-hand corner of Figure 5.1 indicate, absolute C/A- and P-code navigation solutions using conventional pseudo-ranging techniques provide three distinct levels of accuracy, de-

THE SIX BASIC LEVELS OF GPS ACCURACY

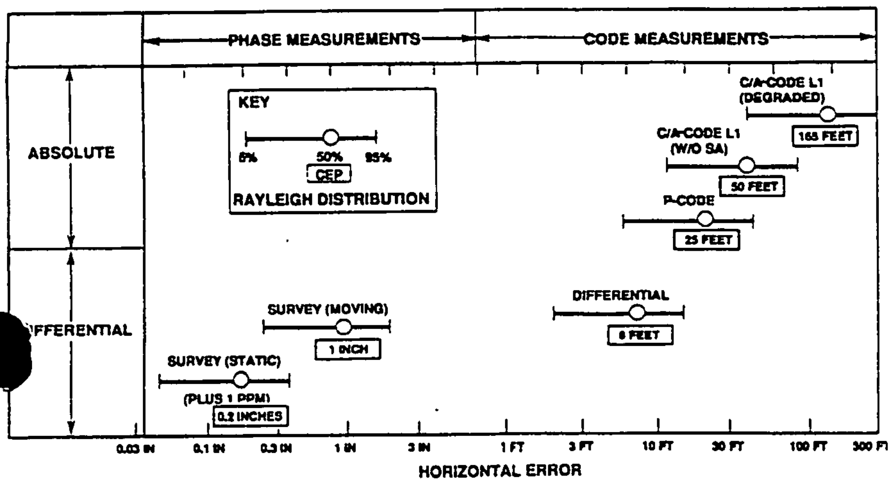


Figure 5.1 The average positioning error of a Navstar receiver depends primarily on the type of signal it is processing (C/A- or P-code), its status with respect to selective availability (degraded or undegraded), and whether or not it is using differential navigation and/or carrier aiding techniques. The six horizontal bars in this figure represent six popular modes of navigation presently being employed by users of various types. Notice that their average (CEP) errors range from 0.2 inches to 165 feet—a variation that spans five orders of magnitude!

pending on the precise method of implementation. Each horizontal stripe spans 90 percent of the navigation errors in a Rayleigh distribution. The Rayleigh distribution function is often used to model radial navigation errors. It resembles the familiar "bell-shaped" distribution curve, with a slight tilt to the right. The small circles near the center of each horizontal stripe mark the most probable navigation error (CEP value) for that particularly mode of navigation. The stripe itself represents ± 45 percent of the cases on either side of the CEP value.

The stripe at the top and to the far right of Figure 5.1 represents the case in which a C/A-code receiver is operated in the degraded mode (with selective availability implemented). In this case the CEP positioning error turns out to be about 165 feet, but under worst case conditions (95 percent probability level), the error can be as large as 330 feet. The undegraded C/A-code solution (without selective availability) is represented by the second bar from the top. In this case the CEP value turns out to be 50 feet, with a "worst case" error of 100 feet. This compares rather favorably with the undegraded P-code solution (third bar from the top), which yields a CEP navigation error of 25 feet.

When a receiver is operated in the differential navigation mode, with relatively gentle vehicle dynamics, a differential navigation solution (fourth bar) typically provides a CEP positioning error of 8 feet or less. In this case, of course, the positioning error is measured with respect to the differential base station not in absolute map coordinates. For slowly moving survey-type solutions with efficient carrier wave aiding (fifth bar), the CEP error shrinks to only about one inch. In a carrier-aided solution, the Navstar receiver uses L_1 and/or L_2 carrier wave measurements to enhance the accuracy of its differential navigation solution. Methods for implementing carrier-aided solutions are discussed in detail in the first half of Chapter 7.

The sixth and final bar in Figure 5.1 represents the case in which carrier-aided navigation solutions are executed by a static user who occupies a fixed survey site for 15 to 45 minutes. In this case the average navigation error can be reduced to only about 0.2 inches, assuming that the receiver and its base station are sufficiently close together. For appreciable separation distances, the surveying error increases by one part per million. This means that the distance in inches between the base station and survey site must be divided by 1 million and then added to the 0.2-inch value to obtain the actual average error. Thus, if base station and survey site are 1 million inches apart (about 16 miles), the total positioning error will amount to 1.2 inches.

Performance Criteria to Consider when Purchasing a Navstar Receiver

When you have decided to purchase a Navstar receiver specifically suited to your particular needs, you should take into account various design parameters and measures of performance before making your final selection. Here are three important measures of performance, each of which is affected by a variety of design decisions:

1. Navigation accuracy
2. Dynamic operating capabilities
3. Jamming immunity

The *navigation accuracy* for a particular receiver provides a quantifiable measure of its likely positioning errors when it is used to obtain a navigation solution. Military specifications for the Navstar navigation system call for a P-code positioning error not to exceed 50 feet CEP. Similar performance specifications for civilian navigation users call for a degraded C/A-code navigation error of 100 meters or less 95 percent of the time. As we have seen in previous paragraphs, differential navigation and carrier-aided solutions can result in much smaller average errors.

The *dynamic operating capabilities* of a Navstar receiver provide us with a convenient numerical measure of its anticipated behavior when it is operated in a vehicle with uncertain dynamics. Single-channel C/A-code receiv-

ers often experience degraded operation (or cease to function entirely) when they are subjected to only a few g's. They lose lock on the satellite signals in relatively undemanding dynamic environments, or else they provide inaccurate or erratic navigation solutions. More complicated multichannel P-code receivers can usually operate in high-dynamic environments without serious difficulty.

The *jamming immunity* of a Navstar receiver provides us with a quantifiable measure of its resistance to inadvertent or purposeful (enemy) jamming. P-code receivers usually have much higher jamming immunity than C/A-code receivers. The jamming immunity of both types of receivers can be enhanced by various practical measures, such as terrain masking, null-steering antenna, or careful integration with an inertial navigation system.

ceiver Design Choices

Once you have decided to design or purchase a Navstar receiver, you will need to focus your attention on certain specific design choices in attempting to obtain the most suitable unit at the most affordable price. These design choices, which are discussed in the next few paragraphs, can be grouped into four broad categories:

1. Number of channels and sequencing rate
2. Access to selective availability signals
3. Available performance enhancement techniques
4. Computer processing capabilities

Each of these four categories is further subdivided and explored in the next four subsections. Then, in a later section, their various impacts are summarized in a convenient tabular format.

Number of Channels and Sequencing Rate

As Chapter 4 indicates, three major types of receivers are currently available in the commercial marketplace:

1. Continuous-tracking receivers
2. Slow-sequencing receivers
3. Fast-sequencing receivers

Continuous-tracking receivers are typically rigged with 4 to 12 parallel processing channels, each of which devotes itself to a particular satellite at a particular time. While it is tracking a given satellite, the continuous-tracking receiver measures the signal travel time and the instantaneous Doppler shift. It also decodes the satellite's 50-bit-per-second data stream to gain access its ephemeris constants, its clock correction factors, and any relevant health status information.

A continuous-tracking receiver with four or more channels can provide accurate navigation, high-dynamic operation, and good jamming immunity, but, compared with the other two options, it tends to be costly and complicated. "All-in-view" receivers are even more complicated because they perform their navigation solutions using pseudo-ranging measurements from all of the satellites currently situated above the horizon. An all-in-view receiver typically provides a 20-percent reduction in average navigation error, compared with a receiver that processes the signals from only four satellites. Unfortunately, the largest error reductions occur when several satellites are in view and the solution errors are fairly small. When coverage is skimpy, the all-in-view receiver does not provide much improvement.

Slow-sequencing receivers are considerably cheaper than continuous-tracking receivers, but their performance is degraded in the presence of moderately strong jamming signals, and they do not operate well in high-dynamic environments. For some applications a slightly more complicated two-channel receiver can provide a reasonable design compromise. The second channel can "rove" among the available satellites to establish their signal characteristics and gain access to their current ephemeris constants. Thus, only minimal delays are experienced when a new satellite must be phased in to take over for one that has passed below the horizon or moved into an unfavorable location with bad geometry.

Fast sequencing receivers also use time-sharing techniques, but they dwell on each satellite for an extremely brief interval (typically one two-hundredth of a second) before switching to the next satellite in sequence. "Multiplexing" receivers of this type provide an interesting compromise between the continuous-tracking and the slow-sequencing designs. They can operate under fairly high dynamic conditions, and their somewhat shorter time-to-first-fix is acceptable in many situations. Unfortunately, multiplexing design makes such a receiver considerably more susceptible to enemy jamming, and, hence, it tends to be a poor choice for high-performance military applications.

Access to Selective-availability Signals

When building or purchasing a Navstar receiver, the serious user must determine whether it will be rigged with L_2 signal processing capabilities. If it is available, the L_2 signal can yield dual-frequency ionospheric corrections that improve the accuracy of that particular component of the pseudo-ranging error budget by a factor three compared with the polynomial correction provided by a simpler L_1 receiver. Of course, becoming an authorized user with access to the L_2 signal may be quite difficult. So far, only military users and a few others who can justify their needs have been granted

access to the P-code signals—which are the only pseudorandom pulse sequences available on L_2.

The error growth rate for very-long-baseline surveying could be substantially reduced if interferometry-type receivers could be rigged to process the L_2 signals. With a single-frequency L_1 receiver, typical surveying errors amount to about 0.2 inches plus 1 part per million. But, if both the L_1 and the L_2 signals are available, the error growth rates are typically reduced to 0.2 inches plus only 0.5 parts per million. The on-site averaging time for surveying solutions can also be reduced when the L_2 signal is available. A benchmark that requires 45 minutes of averaging time using the L_1 signal typically requires only 15 minutes of averaging time when both the L_1 and the L_2 signals can be used in obtaining the navigation solution.

Code selections must also be taken into account when selecting the number of channels and the sequencing rate for a Navstar receiver. Three fundamentally different approaches are available:

1. C/A-code compatibility
2. P-code compatibility
3. Code-free navigation solutions

Each of these three different selections has its own relative advantages and disadvantages.

C/A-code receivers are cheap and simple. They work well in low-dynamic environments where purposeful or inadvertent jamming signals are not a problem. However, when military encryption is imposed on the L-band signals, the C/A-code selection is the only practical choice for most users because, in that case, the P-code transmissions will be available only to authorized (military) users.

The P-code has a higher chipping rate than the C/A-code, so it provides smaller navigation errors, better jamming immunity, and improved multipath rejection. To obtain the full accuracy of the Navstar system, military P-code users must gain access to the proper encryption keys to eliminate the effect of anti-spoofing and selective availability.

Code-free (carrier-aided) receivers, which are also called "interferometry" receivers, skirt this worrisome thicket of difficulties by making use of their own base stations to gain access to the extra accuracy provided by the L_1 and L_2 carrier waves. Under favorable conditions, codeless interferometry receivers can provide extreme accuracy. Unfortunately, they suffer from severe performance penalties in terms of the signal-to-noise ratio. For this reason an interferometry receiver tends to be a poor choice for a demanding military mission.

Selective availability was turned on for the Block II satellites. Then it was turned off during the Persian Gulf War to allow coalition forces to use plentiful and inexpensive civilian receivers. Then it was turned back on again when the war was over. Consequently, today's authorized users must have access to the proper electronic equipment and the necessary encryption

keys in order to restore the full P-code accuracy of the Navstar system. If the proper encryption keys are not available, the positioning accuracy will be degraded—unless U.S. military experts should, for some reason, decide to turn selective availability off again.

Available Performance Enhancement Techniques

A number of techniques are available for enhancing the performance capabilities of a Navstar navigation receiver. These include the use of differential navigation, pseudo-satellites, and aiding inputs from barometric altimeters, atomic clocks, and integrated navigation systems—all of which can substantially enhance the reliability and robustness of the navigation solutions. Of course, these performance enhancement techniques can be implemented only if the receiver has been designed to accept the necessary inputs.

If, for instance, a receiver is to be operated in the differential navigation mode to obtain improved accuracy, it must be equipped with dedicated software and special interface ports for receiving the pseudo-range corrections from the differential base station, most likely in the formats specified by Special Committee 104.

Special Committee 104 was formed by the U.S. Department of Transportation, and its recommended data exchange protocols have been widely reported in *The Journal of The Institute of Navigation* (Washington, D.C.).[1] The Committee includes government and industry participants who develop guidelines to help foster widespread adoption of differential correction techniques. The Committee's most important assignment is to devise standardized data exchange protocols and signal formats for the differential navigation messages. Their message format calls for the broadcast of a 50-bit-per-second data stream from each differential base station, using protocols that are surprisingly similar to the data stream broadcast by the Navstar satellites. Most of the time the differential base station broadcasts real-time pseudo-range corrections, but occasionally it interleaves other types of information.

In order to achieve full differential navigation accuracy, navigators must use continuous-tracking multichannel Navstar receivers. Dual-sequencing receivers are not nearly as accurate when they are used in connection with differential navigation. In most cases the differential navigation solutions recommended by Special Committee 104 are considerably more accurate than the usual absolute navigation solutions only if the user is within two or three hundred miles of the differential base station. The users must receive and process the differential navigation corrections quickly, because their effectiveness degrades with time. These and other issues are further discussed in Chapter 6.

[1]The address and phone number of the Institute of Navigation are listed in Appendix C.

Pseudo-satellites are "false" satellites that sit on the ground at fixed locations and transmit navigation signals similar to the ones transmitted by the Navstar satellites. This approach can substantially improve the user's navigation accuracy, especially altitude accuracy. Properly equipped pseudo-satellites can also help insure the integrity of the signals streaming down from the GPS satellites orbiting overhead. Specially designed Navstar receivers with the proper hardware and software modules are required if the user is to take advantage of the signals being broadcast by the ground-based pseudo-satellites. Recommended signal specifications and data formats for pseudo-satellite transmissions have also been developed by Special Committee 104. Pseudo-satellites transmit in the L-band portion of the frequency spectrum, but, unlike the L-band signals from the satellites, they employ pulse-position modulation. In pulse-position modulation the transmitter is activated (transmitting) only a small fraction of the time. This minimizes the jamming of nearby receivers.

Even if a Navstar receiver is not designed to use the pseudo-satellite signals, it should be designed for *pseudo-satellite immunity*. Otherwise, inadvertent jamming of the satellite signals may occur whenever the user approaches one of the pseudo-satellites. The signal formats and the message exchange techniques recommended by Special Committee 104 have been carefully structured to help minimize interference from pseudo-satellites. Nevertheless, any individual who buys a modern Navstar receiver should obtain assurances of pseudo-satellite immunity before making a commitment for final purchase.

Computer Processing Capabilities

A well-designed Navstar receiver must include appropriate software modules to enhance its accuracy, stability, and reliability. Powerful and robust Kalman filtering techniques and satellite selection algorithms are especially important. A properly designed Kalman filter should include static operating capabilities, together with properly programmed adjustments for operation in different acceleration environments. It should also be able to solve for velocity, make proper use of altitude aiding, and provide frequent updates to refresh the Kalman filter before its gains and constants become stale. Kalman filter design is both science and art, and different applications and operating environments call for grossly different Kalman filters.

The satellite selection algorithm should be refreshed at least once per minute. Each time it is refreshed it should take into account the health status of all the available satellites and a large array of GDOP (Geometrical Dilution of Precision) values. All-in-view receivers, which pick up and process the L-band signals from all the visible satellites, should examine a similar array of factors in determining which (if any) navigation signals they choose to ignore and what weights they should assign to the signals they choose to use in their overdetermined solutions.

External navigation aids, such as altimeters, inertial navigation systems, atomic clocks, and other ground-based and space-based navigation systems, can greatly improve the stability, the accuracy, and the jamming immunity of a real-time navigation solution. External navigation aids can also help increase the receiver's integrity and reliability, thus opening up many demanding uses for the Navstar navigation system, including automotive position-fixing and air traffic control that might, otherwise, be too hazardous or too politically sensitive for widespread adoption.

Receiver Design Smart Card

The "smart card" in Table 5.1 summarizes some of the major design choices that should be considered when purchasing or constructing a new Navstar receiver. Each column highlights the specific effects of ten design choices on the accuracy, the dynamic response, and the jamming immunity of the various kinds of Navstar receivers available in today's competitive marketplace.

Notice that all ten of the design choices impact the accuracy of the navigation solution, with the exception of pseudo-satellite immunity, which allows a nonparticipating receiver to operate in the vicinity of pseudo-satellites. By contrast, only four of the design choices impact the jamming immunity and only three of them impact dynamic response: (1) the number of channels, (2) Kalman filtering and update rate, and (3) aiding inputs. One way to benefit from this smart card is to decide which of the basic measures of performance—accuracy, dynamic response, jamming immunity—are important to you, and then go down the appropriate column to pick out those specific design techniques that might improve your particular situation. A more detailed review of the relevant parameters can then help point the way toward various methods for achieving your performance goals at the most affordable price.

Today's Available Navstar Receivers

Forty large companies throughout the world are today producing and marketing Navstar receivers. All together, they offer more than 100 different models, 75 percent of which can provide civilian C/A-code positioning solutions.

Land-based navigation services are provided by about 77 percent of the commercially available receivers. Marine and aeronautical applications are served by 63 and 57 percent of them, respectively. Although the Navstar constellation is financed by military dollars, only 15 percent of today's receivers are designed for military applications.

The most popular units are 1-, 2-, and 5-channel models, but channel numbers ranging from 1 through 12 are all available—with the possible

Table 5.1 Smart Ca[illegible]sign Choices

Design Parameters	*Accuracy*	*Dynamic Response*	*Jamming Immunity*
1. No. Of Channels And Sequencing Rate	Mulit-Channel And Multiplexing Receivers More Accurate In Dynamic Situations	Multi Channel Receivers More Accurate In Dynamic Situations	Multiplexing Receivers More Suceptable To RF Jamming
2. L_2 Capability	L_2 Receivers Provide Dual-Frequency Ionospheric Correction L_2 Receivers More Accurate For Surveying		
3. Code Selections C/A, P, or Codeless	P-Code Receivers More Accurate Codeless Receivers Substantially More Accurate		P-Code Receivers More Immune To Jamming Codeless Receivers More Suceptable To Jamming
4. Access to SA Signals	Access To SA Keys Restores Full P-Code Accuracy		
5. Differential Compatibly	Differential Navigation Provides Substantial Accuracy Improvements		
6. Pseudo-Satellite Compatibility	Pseudo-Satellite Navigation Provides Substantial Accuracy Improvements		
7. Pseudo-Satellite Immunity			Design-Immunity To Pseudo-Satellites Prevents Inadvertent Jamming
8. Kalman Filtering And Update Rate	Sophisticated Kalman Filtering Improves Nav. Accuracy And Flexibility	Sophisticated Kalman Filtering With Frequent Updating Improves Dynamic Response	
9. Satellite Selection	Frequent Updating Of Satellite Selection Improves Nav. Accuracy		
10. Aiding Inputs	Real-Time Aiding With Altimeters, Atomic Clocks, etc, Improves Nav. Accuracy	Velocity Measurements With Inertial Navigation System Can Improve Dynamic Response	Velocity Aiding With Inertial Navigation System Can Improve Jamming Immunity

exception of an 11-channel receiver. Some hand-held units weigh only a few ounces each, whereas some larger models weigh as much as 100 pounds or more. The heaviest units serve as base stations for differential navigation, so they are both receivers and transmitters. For this application, miniaturization is not particularly desirable because a differential base station sits permanently at one location on the ground. Power levels of today's receivers range from fractions of a watt up to 200 watts or more. The power-hungry units are, most often, differential navigation transceivers.

Various types of interface ports are available, but the most popular version is the RS-232 interface port. The IEEE-488 Centronics port is also widely used, as is the KYK-13 military interface port, which is equipped to handle encrypted inputs.

Hand-held Receivers

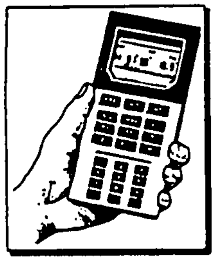
A typical Navstar receiver is about the size of a portable electric typewriter. But, in general, modern versions are getting smaller and smaller, and hand-held units are also being introduced by a number of manufacturers. The first hand-held receiver was affectionately nicknamed the "Virginia Slim" because it was about the same size as a king-size pack of cigarettes. This pioneering device was developed in Cedar Rapids, Iowa, at the Collins Division of Rockwell International under a special contract to DARPA (Defense Advanced Research Project Agency). DARPA researchers frequently sponsor high-risk research projects with the potential for big military payoffs. The Virginia Slim is a 2-channel, dual-frequency P-code receiver weighing about 8 ounces (not counting battery weight). It uses the latest custom-designed gallium-arsenide circuit chips. Chips made from gallium-arsenide are costly and difficult to produce, but they have unusually high switching speeds and good resistance to nuclear radiation.

Another popular hand-held unit, the Magellan Nav 1000 GPS receiver, was originally designed for use aboard pleasure boats, but it was widely used in Saudi Arabia and Kuwait by coalition forces fighting in the Persian Gulf. The Magellan Nav 1000 (see Figure 5.2) weighs 28 ounces and is powered by six AA alkaline batteries. During the Persian Gulf War it retailed for less than $3,000 per unit with a one-year guarantee.

The Nav 1000 features convenient alphanumeric displays with 50 user-supplied waypoints. At the push of a button it provides the user with current range and bearing to the next waypoint. Magellan's receiver is rigged to compute satellite availability anywhere in the world and to evaluate L-band signal strength and satellite geometry. Also, like a bar of Ivory soap, it floats! The designers built it with positive buoyancy so, if a navigator accidently drops it overboard, it can be retrieved.

Hand-held receivers in a variety of configurations are becoming widely available, including one from Japan's Sony Corporation. Excitement rippled through the marketplace when early newspaper reports indicated that the

THE MAGELLAN GPS NAV 1000 HAND-HELD RECEIVER



RECEIVER CHARACTERISTICS

- WEIGHT = 28 OUNCES
- POWER = 6 AA ALKALINE BATTERIES
- PRICE - $2,000
- GUARANTEE = 1 YEAR

PERFORMANCE FEATURES

- 50 WAYPOINTS
- RANGE AND BEARING TO YOUR DESTINATION
- TIME TO GO AND ESTIMATED TIME OF ARRIVAL
- CROSS TRACK ERROR

NAVIGATION MADE EASY

- AUTOMATIC SATELLITE SELECTION
- COMPUTES SATELLITE AVAILABILITY ANYWHERE IN THE WORLD
- WAKE-UP ALARM TO TAKE POSITION FIX

Figure 5.2 Magellan's Nav 1000 hand-held receiver, a civilian maritime unit, was widely used by coalition forces during the war with Iraq. It features simple alphanumeric displays, waypoint navigation with 50 user-supplied longitude/latitude waypoints, and a lightweight, compact design. Powered by six ordinary AAA alkaline batteries, the Nav 1000 sold for less than $3,000 at marine supply houses during the Persian Gulf war.

Sony's 4-channel C/A-code receiver would retail for $690, or about one-quarter the cost of competitive hand-held units. Unfortunately, later marketing announcements from Sony fixed the introductory price at $1,300 per unit. Trimble Navigation, Columbia Positioning, and Standard Electrik in Germany are also producing hand-held devices for the personal navigation market.

Commercially Available Navstar Chipsets

Most commercially available Navstar receivers are full-blown devices complete with L-band antennas, software routines, power sources, and control display units. But a few of them are being sold as "chipsets," which include only the solid-state electronic devices that fit inside Navstar receivers. Chipsets are sold primarily to other manufacturers who integrate them with their own antennas, batteries, and other modules before selling them to the end user.

The Navcore V, being marketed by Rockwell International, provides an illustrative example. Navcore V, which is about the same size as an ordinary playing card, features the latest gallium-arsenide technology with custom-integrated circuit chips. It includes 2 megabytes of read-only memory with two low-density random-access circuit chips. When integrated with other appropriate modules, it functions as a 2-channel Navstar receiver. Single Navcore V chipsets sell for $450 each, with mass production quantities available for only $225 per unit.

Magellan Systems Corporation has produced a slightly larger 5-channel GPS receiver module on a two-board set pinned back-to-back. Magellan's device can operate in a 2-g acceleration environment at a velocity of 1000 miles per hour while providing a position update once per second throughout its flight.

Motorola's 6-channel parallel receiver provides one position update per second in a 4-g environment at a velocity of 670 miles per hour. It can be powered by a 1.5-watt DC power supply operating at 5 volts, or it can be plugged into any standard automotive electrical system.

Navstar Electronics in Sarasota, Florida (a subsidiary of Navstar, Ltd., in Daventry, England), markets the Navstar XR4-PC Insertion Card, which can be plugged directly into an IBM Personal Computer (AT or XT model or an equivalent IBM-PC clone). The Navstar Insertion Card draws its power from the PC motherboard, but, when it is operating, it does not disturb the normal operation of the computer. Once it has been installed, the XR4-PC functions as a 2-channel multiplexing receiver capable of tracking up to eight GPS satellites. The position, velocity, and timing measurements it provides can be fed directly into the computer for processing by any commercially available software routines (spreadsheets, databases, etc.) or by custom software developed by the user. A number of imaginative applications will likely emerge once this cleverly designed device is widely available in universities, laboratories, and research centers throughout the technological world.

6

Differential Navigation and Pseudo-satellites

The Navstar GPS is considerably more accurate than most other radio navigation systems. But, even with P-code precision, its pseudo-ranging solutions do not offer sufficient accuracy for some demanding applications, such as carrier landing operations and maritime navigation in inland waterways and constricted harbors. Fortunately, a number of large research groups, including the United States Coast Guard, are attempting to perfect differential navigation to enhance the system's accuracy for these and many other equally demanding applications.

A differential navigation system uses two Navstar receivers that continuously exchange navigation information with one another in real time. One of them acts as a "base station"; the other navigates relative to the base station's location. In effect, the mobile receiver differences between the two real-time navigation solutions, thus eliminating many of their common errors. Satellite ephemeris and clock-bias errors, for instance, tend to be common to the two solutions. To some extent commonality also exists between the ionospheric and tropospheric delays, which are induced as the L-band signals travel from the satellites down toward the ground. The few remaining line-of-sight ranging errors that are not common to the two solutions tend to be relatively small.

Recent tests indicate that, in some cases, differential positioning errors as small as 3 to 6 feet or smaller can be achieved. The actual error depends on the distance between the two receivers, the speed with which the relevant data can be exchanged, and the sophistication of the computer processing techniques, including, of course, the necessary Kalman filters.

Performance Comparisons: Absolute and Differential Navigation

Early computer simulations using an eight-state Kalman filter to model the behavior of a military jet landing on an aircraft carrier confirmed that the differential navigation errors could be as small as 3 to 6 feet. This result was obtained using theoretical computer situations, but actual flight tests with differential navigation have demonstrated that it accurately reflects the real-world situation.

Figure 6.1 compares the accuracy of absolute and differential navigation for a flight in which an airplane was flying around an oval-shaped "racecourse" trajectory. Notice that, during the initial portion of the flight when absolute navigation was being used, the navigation errors were approximately 120 feet in altitude and a little over 60 feet in the horizontal plane. When differential navigation was implemented, both errors were quickly

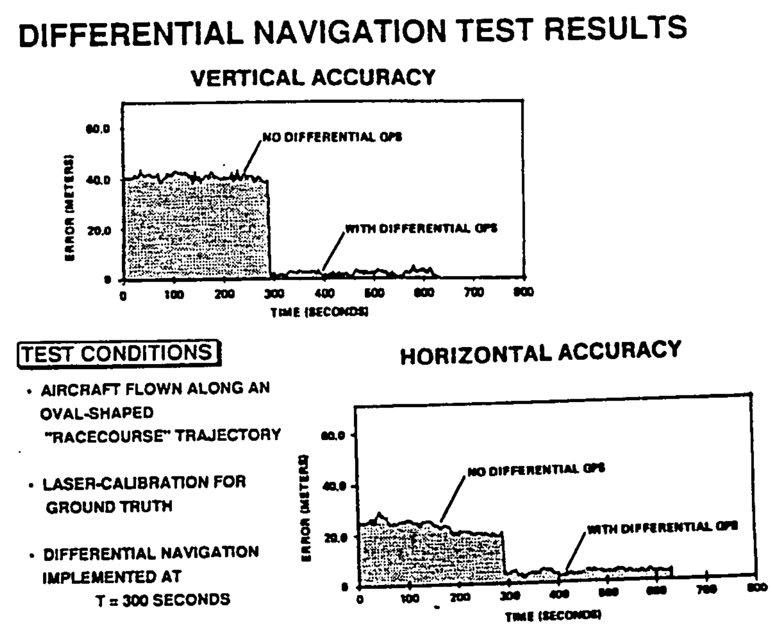


Figure 6.1 In this test series a special airplane was flown around an oval "racecourse" trajectory to test the comparative accuracies of absolute and differential navigation. Both types of navigation solutions were calibrated using precision laser-ranging devices located on the ground. For the first 300 seconds, absolute GPS navigation provided average errors of approximately 120 feet in altitude and 60 feet in the horizontal plane. At $t = 300$ seconds, differential navigation was implemented. The relative error was then quickly reduced to only about 10 feet.

reduced to 10 feet or less. In recent years a number of similar tests, using various types of hardware and software, have achieved comparable results.

Special Committee 104's Recommended Data-exchange Protocols

In order to encourage widespread adoption of differential navigation, Special Committee 104 has released special data exchange protocols and message formats for the differential navigation corrections.[1] The standardized formats recommended by the committee will allow the differential corrections to be transmitted from base stations at various locations to nearby users in a form they can accept and process as they move from the vicinity of one differential base station to another. The signal formats chosen by the Committee are, in many respects, similar to the navigation data stream broadcast by the Navstar satellites. In particular, the Committee's recommendations call for a 50-bit-per-second data stream using phase-shift-key modulation to mark the boundaries between binary 0s and 1s. The parity checking schemes are also similar, but certain crucial differences do exist between the two types of messages. For one thing, the differential corrections employ a variable word length format. Variable length data words utilize the available bandwidth more efficiently, but the resulting messages are a little more complicated because extra bits must be inserted in the transmission to signal the user when the end of a data word has been reached.

Another important difference is that the message exchange protocols for differential navigation are not limited to a single message type. They include, in fact, a total of 16 different message types. Most of the time the base station transmits pseudo-range corrections (to be explained later). The other 15 message types are occasionally interleaved with these routine differential corrections to provide the user with other useful bits of information, such as the current status of the Navstar constellation, the locations of currently available pseudo-satellites, and the like. The 16 different message types are listed in Figure 6.2, together with a detailed subframe-by-subframe breakdown of message type 1, the primary message type that features pseudo-range corrections and range-rate corrections.

As the sketches in Figure 6.3 indicate, the differential base station obtains its pseudo-range corrections by comparing its conventional real-time pseudo-range measurements with another kind of pseudo-range estimate. The second type of pseudo-range estimate is obtained by subtracting its pre-surveyed location from the satellite's known location. These real-time

[1] Special Committee 104 was instituted by the Radio Technical Committee for Maritime Applications (RTCM), which is managed by the Department of Transportation. Its recommendations are strongly influenced by other government bureaus, consultants, and industry representatives.

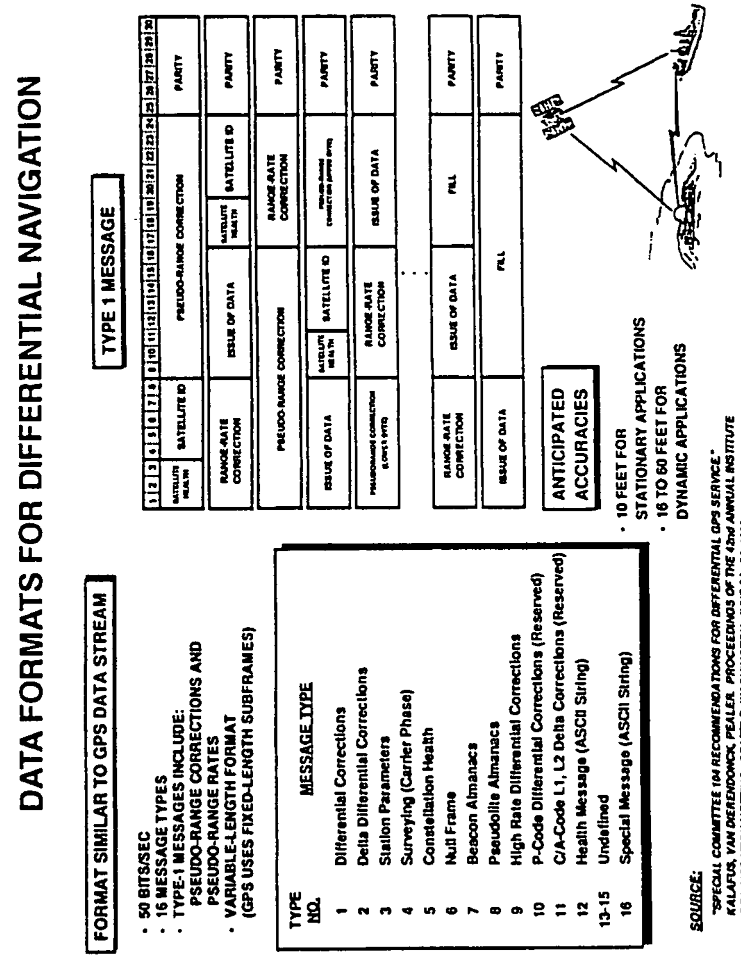


Figure 6.2 Special Committee 104's recommended data exchange protocols for differential navigation include 16 different message types. Most of the time the station broadcasts message type 1, which features pseudo-range corrections and range-rate corrections. The other 15 message types—which provide supplementary information such as base station locations and health status messages—are occasionally interleaved with message type 1.

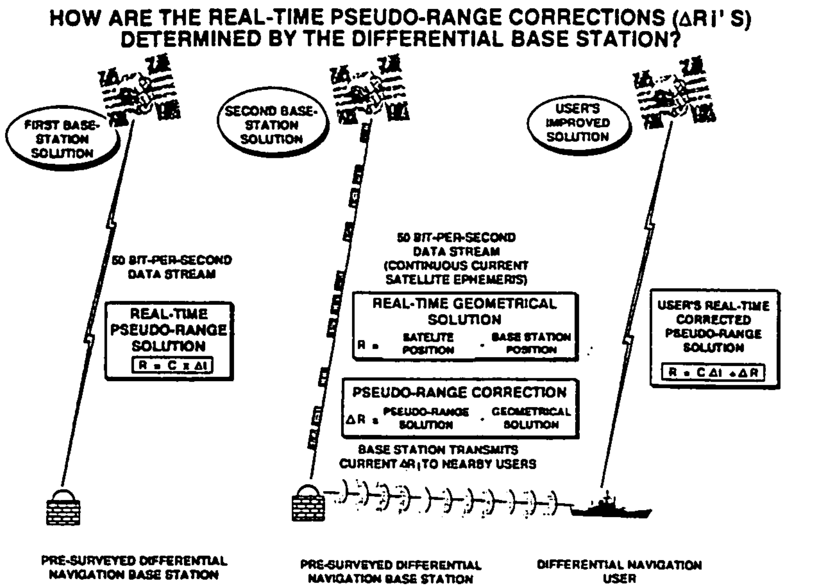


Figure 6.3 A differential base station helps nearby users improve their navigation accuracies by sending them real-time pseudo-range corrections (ΔRi's). The base station determines these corrections by solving for the range to the satellite in two different ways, and then differencing between the two. In the first range solution it measures the signal travel time multiplied by the speed of light. In the second range solution it subtracts the satellite position (computed by using the ephemeris constants) from its pre-surveyed location. Then it differences between the two to get the pseudo-range correction.

pseudo-range corrections are then transmitted to each nearby Navstar receiver, which algebraically adds the appropriate corrections to its current pseudo-ranging solution. This allows it to obtain an improved estimate of its current position.

Field test results indicate that Special Committee 104's data exchange protocols yield differential navigation errors as small as 10 feet for essentially stationary users. For moving users with reasonably gentle dynamics, 15 feet is a more realistic average error. These positioning errors are a little larger than the 3- to 6-foot theoretical errors previously quoted, but they are still substantially smaller than the errors associated with absolute navigation, especially the absolute errors obtained when using degraded C/A-code signals. When differential navigation is employed, it greatly reduces the navigation error. Properly implemented, it removes most of the degradation of error that military experts purposely introduce with selective availability. Of course, differential navigation achieves this favorable result only in the vicinity of a differential base station.

The Coast Guard's Differential Navigation System Tests

In order to evaluate the effectiveness of differential navigation and to determine the influences of ionosphere delays and multipath errors, the U.S. Coast Guard has conducted a series of experiments in which they transmitted, received, and processed differential corrections in the specific formats recommended by Special Committee 104. Coast Guard officials also attempted to determine the effects of various data exchange time delays and separation distances on the accuracy of their differential navigation solutions.

A Trimble 4000A navigation receiver and a Magnavox 5-channel T set were used by the Coast Guard for both static and dynamic testing. Their base station was situated at Boston near the offices of the Department of Transportation. The differential navigation receivers were tested in two distant cities: Groton, Connecticut, and Peoria, Illinois, with baselines spanning 100 and 1000 miles, respectively.

The static navigation test resulted in a mean radial horizontal error amounting to 5.9 feet, with a standard deviation of 0.65 feet. The dynamic test produced a mean radial error of 5.6 feet with a standard deviation of 1.65 feet. Thus, the predicted 7-foot static navigation error was easily achieved.

Dynamic navigation tests were also conducted in which a high-speed patrol boat was piloted through Boston Harbor along a big looping figure-8 trajectory about 3,300 feet long. Ground-truth calibration measurements were obtained from a Falcon 4 Mini Ranger, a short-range ground-based radionavigation system often used in connection with dynamic testing.

Table 6.1 highlights the unmodeled pseudo-ranging errors observed by Coast Guard researchers for the two different baseline lengths. Notice that, with a 100-mile baseline, the unmodeled error in the ionospheric delay ranged from 1 to 2 feet. When the baseline was increased to 1,000 miles, the ionospheric delay created a 4- to 6-foot error. The corresponding values for the unmodeled multipath error were 4 feet and 4 to 6 feet for the 100-mile

Table 6.1 The pseudo-range errors associated with differential navigation for two different baseline lengths

Error source	*100-Mile baseline*	*1,000-Mile baseline*
Typical ionospheric pseudo-ranging error	1 to 2 feet	4 to 6 feet
Typical multipath pseudo-ranging error	4 feet	4 to 6 feet
Combined pseudo-range error (RSS)	4.12 to 4.47 feet	5.65 to 8.48 feet

and the 1,000-mile baselines, respectively. These and other, similar test results have helped Coast Guard researchers predict the overall accuracies of various proposed differential navigation systems, determine the required data exchange rates, and establish the maximum practical separation distances between the base stations and users who can benefit from the differential navigation corrections they provide.

Motorola's Mini Ranger Test Results

Clever and effective differential navigation testing of a different sort was recently carried out by researchers at Motorola's production facility in Tempe, Arizona. In that test series company engineers mounted their differential navigation receiver on an electrically powered golf cart and then drove it along great, careless loops in the company parking lot. Calibration for the Mini Ranger's differential navigation system was accomplished with the Falcon 4—a ground-based radionavigation system that has proven to be highly accurate over short operating ranges. Motorola's Mini Ranger can be rigged to operate in the differential mode or, if desired, in the absolute tracking mode. In the test series conducted in the Tempe parking lot, the differential mode was exclusively used.

Before the comparative tests began, the operator drove the electrically powered golf cart in the "locked wheel" mode, which caused it to trace out a tight circle 6 feet in diameter. Later he drove the cart along a zig-zagging trajectory that carried it alternately between the squat concrete car barriers in the company parking lot. One of the test engineers, a Disleyland enthusiast, later dubbed this method of testing "Mr. Toad's Wild Ride" maneuver (see Figure 6.4).

Positioning errors in the differential navigation solution, compared with the Falcon 4 calibration measurements, typically amounted to only about ± 1.6 feet in each of the three mutually orthogonal coordinate axes. Once they had carefully analyzed the data, Motorola engineers were convinced that, by carefully focusing their attention on the systematic oscillations of the vertical component, they could detect the small undulations created by the drainage ditches in the company parking lot.

The Mini Ranger navigation system provides a position update once per second, with a time-to-first-fix of approximately 2 minutes. At the user's option it can operate in the absolute GPS navigation mode in 13 different coordinate systems, including WSG-84, the 1916 Fisher Ellipsoid, and the Australian National Datum Plane.

Similar tests were conducted with a GPS receiver mounted on a gasoline-powered Minivan cruising through the streets of Noordwijk in the Netherlands. When the receiver was operated in the absolute navigation mode, its position fixes were displaced by several dozen feet from the highway, thus conclusively demonstrating that the absolute navigation solutions were exhibiting substantial errors. But, when that same GPS receiver was operated in the differential mode, its measured ground track stayed near the

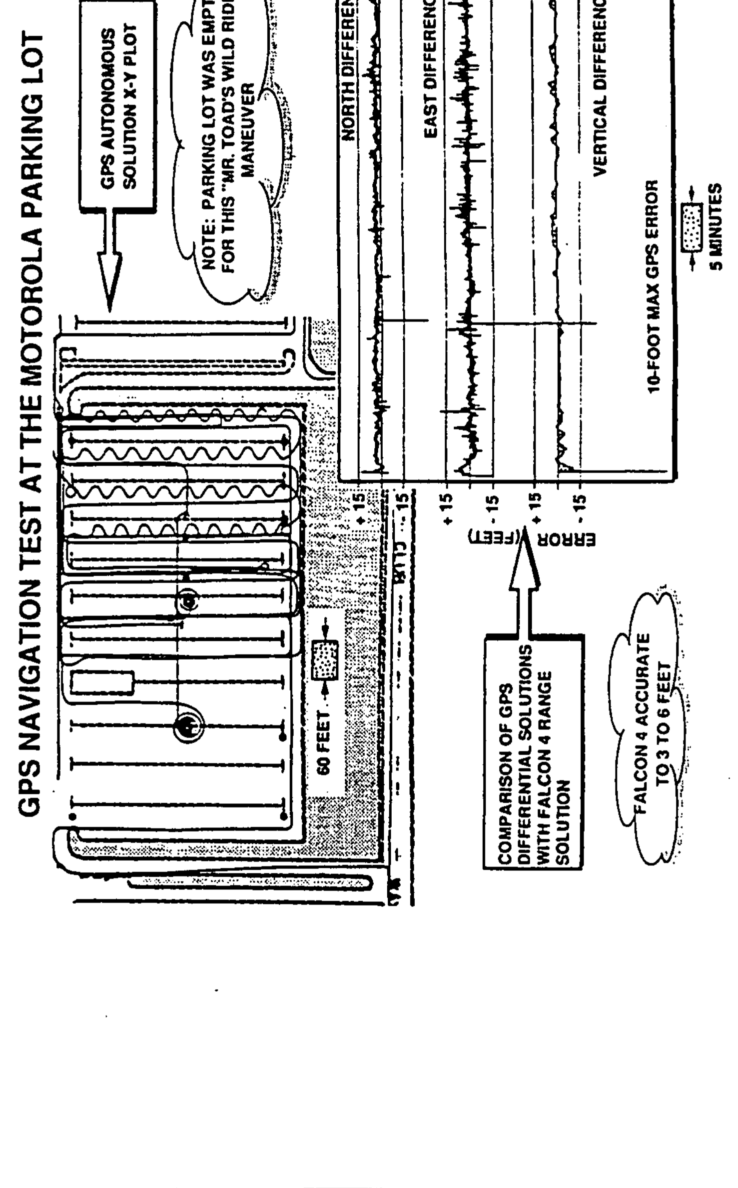


Figure 6.4 "Mr. Toad's Wild Ride" maneuver, as executed in the Motorola parking lot in Tempe, Arizona, demonstrated that differential navigation can produce positioning errors smaller than 10 feet over relatively short baselines. In this test series a differential navigation receiver was mounted on an electrically powered golf cart. The cart was then driven along a zig-zagging trajectory that carried it between alternate pairs of squat concrete barriers in the company parking lot. Accurate ground-truth measurements for the test were provided by the short-range Falcon 4 radionavigation system.

center of the highway with obvious precision. Incidentally, during the Noordwijk test series, the Minivan was driven along the highway at 80 miles an hour, a speed that would have been clearly illegal in any counterpart city in the United States.

COMSAT's Data Distribution Service for the Gulf of Mexico

The COMSAT Corporation, a publicly held entity specializing in communication satellites, recently instituted a space-based service in which differential corrections are broadcast to Navstar users in or near the Gulf of Mexico. So far, the users consist primarily of offshore oil exploration outfits operating seismic exploration vessels on the waters of the Gulf.

The differential corrections originate in Houston, but they are relayed through INMARSAT communication satellites hovering over the equator south of the continental United States. COMSAT's tests indicate that any user within 600 miles of Houston can achieve reasonably accurate differential corrections. Initially, the corrections were distributed free of charge to introduce new users to the system, but subscription fees are now being imposed. If the differential correction service turns out to be a profitable enterprise, COMSAT officials intend to duplicate it in other areas throughout the Western world.

Wide-area Differential Navigation Services

The Coast Guard's field test results indicate that the data exchange protocols recommended by Special Committee 104 provide corrections that lose their effectiveness for users that are located more than a few hundred miles from the differential base station. However, by transmitting more complete arrays of information at faster data exchange rates through orbiting satellites, it may be possible to provide differential corrections that are useable over continent-wide distances. Studies indicate that coverage of this type can be provided for the continental United States, using only about 15 monitor stations, compared with the 500 stations that would be required using conventional differential navigation techniques.

The architecture for the wide area differential navigation system is sketched in Figure 6.5. Notice that, in this approach, simple pseudo-range corrections are not employed. Instead, three other types of correction parameters are broadcast in real-time by the orbiting satellite:

1. Satellite ephemeris corrections
2. Clock bias errors
3. Ionospheric correction terms

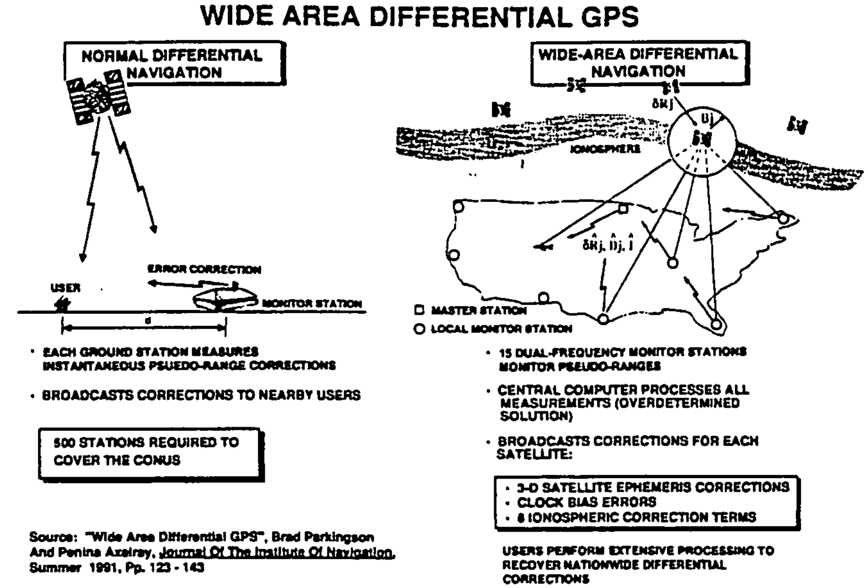


Figure 6.5 Wide-area differential navigation can provide continent-wide differential corrections comparable in accuracy to the corrections provided by conventional differential navigation. However, with this system only 15 widely separated monitor stations are required to cover the continental United States. Three different types of correction parameters must be broadcast by the data distribution satellite: (1) satellite ephemeris corrections, correction data (2) clock bias errors, and (3) ionospheric parameters. When these corrections are used to adjust a real-time navigation solution, the average positioning error shrinks to one-twentieth the comparable error achieved with absolute GPS navigation.

The 15 monitor stations, which are installed at widely separated locations, measure these parameters by picking up the real-time navigation signals from the GPS satellites. Any deviations between the telemetered and the observed satellite ephemeris constants are incorporated in the wide-area differential correction message, together with improved clock corrections and a series of eight constants that define the current continent-wide behavior of the earth's ionosphere.

By applying these three types of corrections to their current navigation solutions, differential navigation receivers all over the country can greatly improve their positioning solutions. Studies indicate that, within a coast-to-coast coverage area, 95-percent error reductions can be anticipated compared with stand-alone GPS navigation solutions.

Pseudo-satellites

Even before any of the Navstar satellites had been launched into space, hundreds of navigation tests had been conducted using GPS-like transmit-

ters positioned on the floor of the desert at Yuma, Arizona. This setup was called "the inverted test range" because airplanes flew over it with belly-mounted navigation antennas rigged to pick up the navigation signals coming toward them from the ground below. Later, when a few of the GPS satellites had been launched into space, navigation solutions were obtained by using a mixture of satellite signals merged with signals from the ground-based transmitters.

Today, ground-based transmitters that mimic the L-band signal format of the GPS are called *pseudo-satellites* (false satellites).[2] Pseudo-satellites broadcast slightly modified versions of the C/A-code transmissions streaming down from the GPS satellites. Many proponents of pseudo-satellites, including members of Special Committee 104, argue convincingly that pseudo-satellites should, in addition, transmit differential corrections to nearby users and also act as monitor stations to help insure the integrity of the conventional GPS satellites.

Dr. Brad Parkinson at Stanford University, who was once in charge of the GPS Program at the Air Force Space Division, set up some of the earliest computer simulations demonstrating the solid benefits that could be achieved by using pseudo-satellites. Dr. Parkinson became interested in pseudo-satellites when he noticed that, under certain conditions, the 18-satellite GPS constellation would occasionally result in a Vertical Dilution of Precision (VDOP) of 12 or even larger in the vicinity of the San Francisco International Airport. A Vertical Dilution of Precision in that magnitude range would create extremely large vertical (altitude) navigation errors. The resulting uncertainty could be especially bothersome if the Navstar signals were to be used for landing operations at airports, large or small.

Brad Parkinson attempted to circumvent this difficulty by running computer simulations in which he introduced a single ground-based pseudo-satellite in the vicinity of the San Francisco airport. Soon he found that the vertical Dilution of Precision was only about 0.7 with one pseudo-satellite. Thus, the use of a pseudo-satellite would greatly increase the safety and reliability of aircraft landings.

Parkinson relied on his computer simulations to determine the best location for the ground-based pseudo-satellite. In his initial studies, he discovered that the most effective location was 30 miles south of the runway. Why 30 miles south of the runway?

Placing a pseudo-satellite immediately adjacent to an airport runway is a bad idea for two reasons:

1. The pseudo-satellite tends to jam the signals coming down from the GPS satellites circling overhead.
2. Navigation accuracy is degraded compared with positioning the pseudo-satellite 30 miles south of the runway.

[2]Some experts shorten the name "pseudo-satellite" to "pseudolite," a cryptic moniker that does nothing but obscure the meaning and confuse the noninitiated.

Parkinson reached this conclusion by trial and error. But later he reasoned that a 30-mile southward location probably produces smaller average errors because the GPS satellites are in 55-degree orbit planes. This places more satellites at high latitudes, so more of them typically lie north of the runway rather than to the south. Thus, a southward location for the ground-based pseudo-satellite tends to provide improved viewing geometry.[3]

Later, during a more detailed study, in which he took a larger number of variables into account—such as radio frequency interference and the local topography—Brad Parkinson found a way to determine the precise optimal location for the pseudo-satellites servicing each specific airport. In this case the best location for a pseudo-satellite is sometimes, but not always, 30 miles south of the runway.

Brad Parkinson is convinced that pseudo-satellite installations can be constructed for $100,000 to $200,000 each, and that America will probably need one or more for each airport of appreciable size. Approximately 6,000 airstrips of various types are in operation in the United States. Most do not have useable landing aids. Pseudo-satellite installations could prove especially beneficial for some of these poorly equipped landing strips.

If the signal structure for the pseudo-satellites is similar to the one employed by the GPS satellites, it can act as an unintended jammer, thus interfering with the proper reception of the L-band signals coming from the GPS satellites. To minimize these jamming effects, some form of time-division multiplexing is necessary, together with careful design for all the GPS receivers to make them more immune to pseudo-satellite jamming.

Special Committee 104's Data Exchange Protocols for Pseudo-satellites

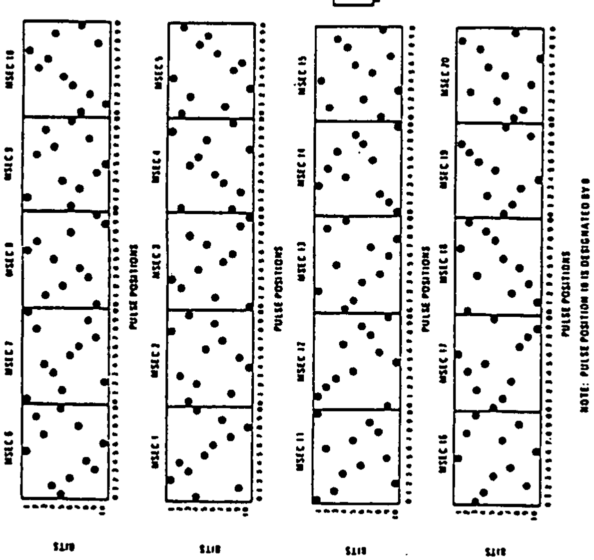
After an extended series of meetings, the members of Special Committee 104 have selected a 1,023-chip Gold Code for the ground-based pseudo-satellites. With the self-jamming problem firmly in mind, committee members have recommended specific pulse-position modulation techniques in which each pseudo-satellite will be active (broadcasting) only about 10 percent of the time. The pseudo-satellite uses the precise timing signals from the GPS constellation to gate itself "on" during scattered 90.91-microsecond intervals (see Figure 6.6). During each gating interval it transmits 93 C/A-code chips so that, after 11 active intervals, its entire 1,023-bit C/A-code has been transmitted. The active intervals are purposely staggered with respect to one another in accordance with the schedule listed schematically on the left-hand side of Figure 6.6.

This specific time-division multiple access technique allows the pseudo-

[3]In the southern hemisphere, the pseudo-satellite should, of course, be positioned *north* of the airport runway.

PS[redacted]-SATELLITE SIGNAL SPEC[redacted]TIONS

PSEUDO-SATELLITE PULSE POSITIONS WITHIN THE 10 DATA BIT, 200-MSEC PATTERN



JAMMING AVOIDANCE

- JAMMING IS AVOIDED BY USING TIME-DIVISION MULTIPLEXING
- 1023-CHIP GOLD CODES ARE USED TO INSURE ORTHOGONAL SIGNAL STRUCTURE
- THE TRANSMITTED PSEUDO-SATELLITE SIGNAL EPOCHS ARE DEFINED TO BE PRECISELY CORRECT IN GPS TIME ($\pm$ 100 η_{sec})

MINIMAL SPACINGS

- PSEUDO-SATELLITES USING THE SAME CODE = 80 TO 180 MILES
- PSEUDO-SATELLITES USING DIFFERENT CODES = 32 MILES

Figure 6.6 In order to avoid jamming nearby GPS receivers, Special Committee 104's pseudo-satellite signal specifications call for the use of pulse-position modulation. With the recommended scheme, each pseudo-satellite transmitter is active only about 10 percent of the time. The pseudo-satellite breaks its 1,023-bit Gold code into eleven 93-chip segments, which are then transmitted during eleven scattered 90.91-microsecond intervals. To avoid mutual interference, pseudo-satellites using different Gold Codes cannot be closer than 32 miles. Those using different Gold Codes must be at least 80 to 180 miles apart.

satellites to transmit their modulated signals only a small fraction of the time so that they create a much smaller jamming hazard for nearby users.

Studies sponsored by Special Committee 104 have shown that two different pseudo-satellites using the same Gold Code cannot be any closer than 80 to 180 miles; otherwise, they will interfere with one another. Two pseudo-satellites using the same Gold Codes cannot be any closer than 32 miles.

The experts from Special Committee 104 have issued practical guidelines for designing and building pseudo-satellite–compatible receivers and pseudo-satellite–immune receivers. A pseudo-satellite–compatible receiver can pick up and use the pseudo-satellite signals to obtain improved navigation accuracy. A pseudo-satellite–immune receiver cannot pick up and use the pseudo-satellite signals, but it can pick up the signals from the GPS satellites, even when it is in the vicinity of an active pseudo-satellite.

The Committee's guidelines emphasize that a successful pseudo-satellite receiver must be able to receive and process the pseudo-satellite signals continuously, so it must be a continuous-tracking multichannel receiver. Of course, the pseudo-satellite receiver must be designed to generate the pseudo-satellite's C/A-code using pulse-position modulation techniques and it must be rigged to perform all necessary computations.

The popular 7-bit ASCII code used in personal computers will be used to encrypt up to four consecutive alphanumeric characters to allow the receiver to figure out which pseudo-satellite is transmitting the Gold Code pulses being received in the L-band portion of the frequency spectrum. The pseudo-satellites near Los Angeles International Airport, for instance, would be denoted by the ASCII symbols LAX1, LAX2, LAX3, and so forth.

Comparisons Between Differential Navigation and Pseudo-satellites

One important advantage of a pseudo-satellite over a differential navigation transmitter is that the pseudo-satellite improves the coverage characteristics and the geometry of the conventional GPS constellation. Pseudo-satellites also provide excellent vertical navigation accuracy. When pseudo-satellites are used, no extra receivers are required. This is true because the (modified) GPS receiver doubles as the pseudo-satellite receiver. In most proposed pseudo-satellite systems, the pseudo-satellite base stations would also transmit real-time differential navigation corrections interleaved with their normal C/A-code transmissions. In addition, they would transmit integrity-related warnings to local users if any of the satellites in the GPS constellation appear to be transmitting inaccurate navigation signals.

One practical disadvantage of pseudo-satellites is that they are limited to line-of-sight coverage. This is true because the transmission must be in the L-band portion of the frequency spectrum which does not reflect off the ionosphere. Pseudo-satellite receivers also require extra hardware modules

and software routines to allow them to choose and identify the pseudo-satellites in their vicinity. Finally, if pseudo-satellite transmitters are widely installed, all critical GPS receivers must be pseudo-satellite compatible. Otherwise, the signals from the GPS satellites may be jammed whenever the receiver is close to a pseudo-satellite.

Additional comparisons between differential navigation and pseudo-satellites are provided in Table 6.2. Notice that the choice of transmission frequencies is more flexible for differential navigation because the transmissions are not constrained to be in the L-band portion of the frequency spectrum. The coverage area for differential navigation typically spans a circle 300 to 500 miles in radius centered around the base station. For pseudo-satellites, only line-of-sight L-band coverage is provided. Depending on the height of the transmitting tower, this range is usually 30 miles or less.

The navigation errors associated with a differential navigation solution depend to some extent on the data exchange rate. Errors typically range from 3 to 30 feet. Pseudo-satellites provide roughly comparable navigation errors in the horizontal plane, but their vertical (altitude) errors are considerably smaller. No worrisome user-set jamming problems arise with the implementation of differential navigation, but with pseudo-satellites the transmitters must be properly spaced and the receivers must be carefully designed to minimize the possibility of satellite jamming by the stronger pseudo-satellite signals. This is true even though the pseudo-satellite base stations will be rigged to transmit their signals using pulse-position modulation techniques.

Table 6.2 Comparison between differential navigation and pseudo-satellites

Comparison criteria	*Differential navigation*	*Pseudo-satellites*
Transmission Frequencies	Various possibilities	L-band transmissions required
Coverage area	Typically 300 to 500 miles	Line-of-sight coverage only (typically 30 miles)
Navigation accuracy	Depends on data exchange rate (typically 3 to 30 feet)	Similar to differential navigation, superior in the vertical dimension
Integrity monitoring	Usually provided	Usually provided
User-set jamming	No additional difficulties	Jamming can be minimized by careful user-set design

7 Interferometry Techniques

Most of today's receivers use the pseudorandom C/A-and P-code pulse sequences broadcast by the GPS satellites to obtain their current positioning solutions. But a more sophisticated technique called *interferometry* derives information for its navigation solutions from the sinusoidal carrier waves coming down from the satellites. Interferometry solutions, which are also called carrier-aided solutions, are more difficult to obtain, but, in situations where they are valid, they can provide surprisingly large reductions in the navigation errors, especially for static and low-dynamic surveying applications. Some spaceborne applications can also benefit from carrier-aided processing techniques.

The Classical Michaelson-Morley Interferometry Experiment

Interferometry methods first received widespread attention when they were used in the famous Michaelson-Morley experiment, which proved conclusively that the ether did not exist. The ether was a fanciful substance that was believed to carry electromagnetic waves through the vacuum of space. Nineteeth century scientists endowed the ether with a number of semi-magical properties, such as complete weightlessness, total transparency, and infinite rigidity. If the ether existed, it surely carried beams of light along with it in some preferred direction. The earth travels around the sun at 67,000 miles per hour, and the sun whirls around the center of the Milky Way Galaxy at an even faster rate. Only by the most improbable coincidence would an earth-based observer be stationary with respect to the ether.